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Conferences 26 June-1 July 206

Exhibition 28-29 June 2016
Edinburgh International Conference Centre

Edinburgh, Scotland, United Kingdom

SPIE. ASTRONOMICAL TELESCOPES + INSTRUMENTATION

DATES
Conferences: 26 June–1 July 2016
Exhibition: 28–29 June 2016

LOCATION
Edinburgh International Conference Centre
Edinburgh, Scotland, United Kingdom

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SPIE would like to express its deepest appreciation to the symposium chairs, conference chairs, program committees, session chairs, and authors who have so generously given their time and advice to make this symposium possible.

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Conference 9904: Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave

SPIE. ASTRONOMICAL TELESCOPES + INSTRUMENTATION

Sunday - Friday 26–1 July 2016

Part of Proceedings of SPIE Vol. 9904 Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave

9904-1, Session 1

The James Webb Space Telescope: observatory status and the path to launch

Michael W. McElwain, Charles W. Bowers, Mark Clampin, Malcolm B. Niedner, NASA Goddard Space Flight Ctr. (United States)

The James Webb Space Telescope (JWST) is a NASA flagship mission that will address multiple science themes including our Universe's first light, the assembly of galaxies, the birth of stars and planetary systems, and planets and the origins of life. The JWST is a large (6.5 m) segmented aperture telescope equipped with near- and mid-infrared instruments (0.6-28 microns), all of which are passively cooled to ~40 K by a 5-layer sunshield while the mid-infrared instrument is actively cooled to 7 K. The JWST will be launched to an L2 orbit aboard a European Space Agency (ESA) supplied Ariane 5 rocket, whose payload volume constraints require that the JWST structure is stowed for launch. JWST is currently in the integration and test phase, with parallel activities on-going across the program such as the integrated science instrument module, optical telescope element, spacecraft, and the sunshield. The JWST deployments to the flight configuration are also undergoing alignment and deployed loads testing. The current estimated JWST performance metrics will be presented, such as the image quality, pointing stability, sensitivity, and stray light backgrounds. The JWST development status and future schedule will be described for the full integration, launch, and commissioning. JWST is an international project with contributions from NASA, ESA, and the Canadian Space Agency (CSA). Northrop Grumman Aerospace Systems is the prime contractor for the JWST, and the Space Telescope Science Institute will serve as the science operations center.

9904-2, Session 1

Status of the JWST optical telescope element

Charles B. Atkinson, Scott C. Texter, Northrop Grumman Aerospace Systems (United States); Lee D. Feinberg, Ritva Keski-Kuha, NASA Goddard Space Flight Ctr. (United States)

Significant progress has been made in the development of the Optical Telescope Element (OTE) for the James Webb Space Telescope (JWST) Observatory. At the time of the conference, the OTE will have been completely assembled, including deployment testing and optics alignment and installation. This paper will discuss those accomplishments.

9904-3, Session 1

JWST telescope integration and test progress

Gary W. Matthews, Tony L. Whitman, Thomas R. Scorse, Harris Corp. (United States); Lee D. Feinberg, Ritva Keski-Kuha, Mark F. Voyton, Juli A. Lander, NASA Goddard Space Flight Ctr. (United States)

The James Webb Space Telescope (JWST) is a 6.5m, segmented, IR telescope that will explore the first light of the universe after the big bang. The JWST Optical Telescope Element (Telescope) integration and test program is well underway. The telescope was completed in the spring of 2016 and the cryogenic test equipment has been through two optical test programs leading up to the final flight verification program. The details of the telescope mirror integration will be provided along with the current status of the flight observatory. In addition, the results of the two optical ground support equipment cryo tests will be shown and how these plans fold into the flight verification program.

9904-4, Session 1

Status of the JWST sunshield and spacecraft bus

Jonathan W. Arenberg, James R. Flynn, Andy Cohen, Northrop Grumman Aerospace Systems (United States); Richard Lynch, James L. Cooper, NASA Goddard Space Flight Ctr. (United States)

This paper reports on the development, manufacture and integration of the James Webb Space Telescope's sunshield and spacecraft bus. Both of these JWST elements have completed design and development testing. This paper will review basic architecture and roles of these systems. Also to be presented is the current state of manufacture, assembly integration and test. This paper will conclude with a look at the road ahead for each subsystem prior to integration with the integrated telescope and instrument elements at Northrop Grumman's Space Park facility in late 2017.

9904-5, Session 2

Status of the James Webb Space Telescope science instrument payload

Matthew A. Greenhouse, NASA Goddard Space Flight Ctr. (United States)

The Integrated Science Instrument Module (ISIM) is the science instrument payload of the JWST and is one of three elements that comprise the JWST space vehicle. It is expected to complete flight qualification testing and delivery for integration with the telescope shortly before this conference. The "as delivered" status of the ISIM system will be presented.

9904-6, Session 2

James Webb Space Telescope optical telescope element: integrated science instrument module (OTIS) status

Lee D. Feinberg, Ritva Keski-Kuha, Mark F. Voyon, Juli A. Lander, NASA Goddard Space Flight Ctr. (United States); Gary W. Matthews, Harris Corp. (United States)

The James Webb Space Telescope Optical Telescope Element (OTE) and

Integrated Science Instrument Module (ISIM) are integrated together to form the OTIS. Once integrated, the OTIS undergoes primary mirror center of curvature optical tests, electrical and operational tests, acoustics and vibration testing at the Goddard Space Flight Center before being shipped to the Johnson Space Center for cryogenic optical testing of the OTIS. In preparation for the cryogenic optical testing, the JWST project has built a Pathfinder telescope and has completed two Optical Ground System Equipment (OGSE) cryogenic optical tests with the Pathfinder. In this paper, we will summarize OTIS optical test results to date and status the final Pathfinder test and the OTIS integration and environmental test preparations.

9904-7, Session 2

Cryo-vacuum testing of the JWST integrated science instrument module (ISIM)

Randy A. Kimble, NASA Goddard Space Flight Ctr. (United States); Maria B. Vila, SGT, Inc. (United States) and NASA Goddard Space Flight Ctr. (United States); Julie M. Van Campen, NASA Goddard Space Flight Ctr. (United States); Stephan M. Birkmann, European Space Research and Technology Ctr. (Netherlands); Brian J. Comber, Comber Thermal Solutions (United States) and NASA Goddard Space Flight Ctr. (United States); Curtis C. Fatig, NASA Goddard Space Flight Ctr. (United States); Alistair C. H. Glasse, UK Astronomy Technology Ctr. (United Kingdom); Stuart D. Glazer, NASA Goddard Space Flight Ctr. (United States); Douglas M. Kelly, The Univ. of Arizona (United States); Steven D. Mann, The Hammers Co. (United States) and NASA Goddard Space Flight Ctr. (United States); Andre' R. Martel, Space Telescope Science Institute (United States) and NRC Herzberg Astronomy and Astrophysics (Canada); Kevin J. Novo-Gradac, SGT, Inc. (United States); Raymond G. Ohl, NASA Goddard Space Flight Ctr. (United States); Konstantin I. Penanen, Jet Propulsion Lab. (United States); Scott O. Rohrbach, NASA Goddard Space Flight Ctr. (United States); Joseph F. Sullivan, Ball Aerospace & Technologies Corp. (United States); Dean Zak, CSRA (United States); Julia Zhou, COM DEV Canada (Canada)

In late 2015/early 2016, a major cryo-vacuum test was carried out for the Integrated Science Instrument Module (ISIM) of the James Webb Space Telescope. This test, executed after the ambient environmental testing program for the ISIM (vibration, acoustics, and electromagnetic interference/compatibility testing) represents the final cryo-certification and calibration test of the ISIM before its delivery for integration with the rest of the JWST observatory.

The ISIM, comprised of the four flight science instruments (the FGS/NIRISS, MIRI, NIRCam, and NIRSpec), a composite support structure, and harness radiator (the preceding all cryogenic), as well as an associated nearby compartment housing warm electronics, was tested in the largest thermal-vacuum chamber of NASA's Goddard Space Flight Center. In this test, the ISIM was exposed to a thermal environment set to match the predicted ISIM environment within the JWST observatory in flight, while being illuminated with a cryo-certified telescope simulator designed to feed the various instruments beams of flight-like wavefront quality, position, chief ray angles, f/#, and pupil location.

Over the roughly 100-day period of the round-the-clock test program (designated CV3, as it was the third in the ISIM cryo-vacuum test series), the fully-integrated flight ISIM system was put through a comprehensive program of thermal, optical, electrical, and operational tests. One particularly important aspect of this final cryo-test was the comparison of optical and thermal performance data taken before the ambient environmental test program (in 2014's CV2 cryo-test program) with the corresponding data taken after, for verification of critical stability requirements. In brief, the goals of CV3 were to verify the ISIM system in its final configuration after environmental exposure and to provide a post-environmental performance baseline, including critical ground calibrations needed for science data processing in flight.

In this paper, we briefly summarize the goals, setup, execution, and key results for this critical JWST milestone.

9904-8, Session 2

Wavefront-sensing demonstration testing of the James Webb Space Telescope (JWST) integrated science instrument module (ISIM)

Randal C. Telfer, Space Telescope Science Institute (United States); D. Scott Acton, J. Scott Knight, Ball Aerospace & Technologies Corp. (United States); Bruce H. Dean, Thomas P. Zielinski, NASA Goddard Space Flight Ctr. (United States); Marshall D. Perrin, Charles-Philippe Lajoie, Space Telescope Science Institute (United States); David L. Aronstein, Jeffrey S. Smith, NASA Goddard Space Flight Ctr. (United States)

This paper describes the analysis of the portion of the James Webb Space Telescope (JWST) Integrated Science Instrument Module (ISIM) cryogenic-vacuum testing dedicated to wavefront sensing (WFS) performance relevant to flight commissioning of the optical telescope element (OTE). These tests provide the most representative wavefront-sensing imagery during ground testing of the ISIM regarding several stages of the commissioning process. Aspects covered include imaging of the JWST pupil with the NIRCam pupil imaging lens (PIL), coarse piston sensing of the primary mirror segments with the NIRCam Dispersed Hartmann Sensors (DHSs), fine piston sensing of the primary mirror segments via focus-diverse phase retrieval using the NIRCam weak lenses, and focus-diverse phase retrieval in all science instruments as part of the field-dependent sensing process known as Multi-Instrument Multi-Field (MIMF). The data are used to demonstrate wavefront-sensing performance with the Wavefront Analysis Software (WAS) designed for JWST commissioning. The test suite also includes final cross-checks, characterization, and calibration of WFS components. Calibrations and cross-checks include distortion of the PIL image, dispersion of the DHS sub-apertures, and power and wavefront error of the weak lenses. In this paper, we discuss the component calibration and cross-check results and the overall wavefront-sensing performance of the WAS on the demonstration data. The results are evaluated by comparison to expected results, analysis with independent algorithms, and consistency checks of the output.

9904-9, Session 3

Stray light field dependence for the James Webb Space Telescope

Paul A. Lightsey, Ball Aerospace & Technologies Corp. (United States)

The James Webb Space Telescope (JWST) is a large space based astronomical telescope that will operate at cryogenic temperatures. The architecture has the telescope exposed to space, with a large sun shield providing thermal isolation and protection from direct illumination from the sun. The instruments will have the capability to observe over a

spectral range from 0.6 um to 29 um wavelengths. Stray light analysis has been performed to characterize the stray light getting to the instrument focal planes from the celestial sky. A Radiance Transfer Function (RTF) is defined for the susceptibility of stray light to sky radiance relative to the observatory frame of reference. The stray light is calculated by overlaying the radiance maps of the celestial sky background (both galactic and zodiacal background) onto the RTF map. The product of the two is summed to obtain the total stray light background at the instrument detectors. The orientation of the observatory for observing a given field location in the sky depends on the direction of the sun, hence the day of the year. The variability of stray light with time of year for observing a given sky locations is determined.

9904-10, Session 3

Preparing for JWST wavefront sensing and control operations

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The James Webb Space Telescope's segmented primary and deployable secondary will be actively controlled to achieve optical alignment, through a complex series of steps that will extend across several months during the observatory's commissioning. This process will require an intricate interplay between individual wavefront sensing and control tasks, instrument-level checkout and commissioning, and observatory-level calibrations, which involves many subsystems across both the observatory and the ground system. Furthermore, commissioning will often exercise observatory capabilities under atypical circumstances, such as fine guiding with unstacked or defocused images, or planning targeted observations in the presence of substantial time-variable offsets to the telescope line of sight. Coordination for this process across the JWST partnership has been conducted through the Wavefront Sensing & Control Operations Working Group. We will describe at a high level the activities of this group, and the resulting detailed commissioning operations plans, supporting software tools development, and ongoing test and rehearsal activities at the Science & Operations Center. These efforts are leading to a robust and well-tested process and preparing the team for an efficient and successful commissioning of JWST's active telescope.

9904-11, Session 3

Hartmann test for the James Webb Space Telescope

J. Scott Knight, Ball Aerospace & Technologies Corp. (United States); Lee D. Feinberg, NASA Goddard Space Flight Ctr. (United States); D. Scott Acton, Ball Aerospace & Technologies Corp. (United States); Tony L. Whitman, Harris Corp. (United States); Koby Z. Smith, Ball Aerospace & Technologies Corp. (United States)

The James Webb Space Telescope (JWST) requires testing of the full optical system in a cryogenic vacuum environment before launch. During recent JWST Pathfinder checkout testing at the Johnson Space Center's (JSC) Chamber A thermal vacuum facility, the vibration in this environment has proven challenging for the baseline test architecture, which uses phase retrieval over the sparse aperture testing of the entire JWST telescope element. However, a strategy that was conceived and tested during the recent JWST Pathfinder testing to utilize classic Hartmann test principles combined with precise mirror mechanisms to provide a testing approach that is robust to the dynamics environment of the cryogenic vacuum chamber. The implementation and sensitivity of this test to perform certain JWST system level optical assessments is similar to using phase retrieval over the sparse aperture test. Prior to the JWST pathfinder test, this Hartmann test concept was implemented on the JWST Test Bed Telescope, which provided the rationale and empirical evidence indicating that this Hartmann style approach would be valuable in supplementing the baseline test approach.

This paper presents the results of the Hartmann approach implemented during the recent Pathfinder test along with the test approach that is currently being considered for the full optical system test of JWST. Comparisons are made between the baseline phase retrieval approach and the Hartmann approach in addition to demonstrating how the two test methodologies support each other to reduce risk during the JWST full optical system test.

9904-12, Session 3

Getting JWST's NIRSpec back in shape

Maurice Te Plate, Peter Rumler, Peter L. Jensen, European Space Research and Technology Ctr. (Netherlands); Robert Eder, Ralf Ehrenwinkler, Frank Merkle, Peter Mosner, Andreas Rödel, Max Speckmaier, Airbus Defence and Space (Germany); Brent Mott, Stephen Snodgrass, Thomas E. Johnson, NASA Goddard Space Flight Ctr. (United States); Stephan M. Birkmann, European Space Research and Technology Ctr. (Netherlands)

The James Webb Space Telescope (JWST) Observatory is the follow-on mission to the Hubble Space Telescope. JWST will be the biggest space telescope ever built and it will lead to astounding scientific breakthroughs. The mission will be launched in 2018. NIRSpec, one of the four instruments on board of the mission, recently underwent a major upgrade. New infrared detectors were installed and the Micro Shutter System (MSA) was replaced as well. The rework was necessary because both systems were found to be degrading. The techniques and procedures that were applied during this campaign will be elaborated. Some first cold test results of the upgraded instrument will be presented as well.

9904-13, Session 3

Slitless spectroscopy with the JWST NIRCam instrument

Thomas P. Greene, NASA Ames Research Ctr. (United States); Laurie Chu, Klaus W. Hodapp, Univ. of Hawai'i (United States); Eiichi Egami, Douglas M. Kelly, Jarron M. Leisenring, Marcia Rieke, The Univ. of Arizona (United States); Massimo Robberto, John Stansberry, Space

Telescope Science Institute (United States)

The James Webb Space Telescope Near-infrared camera (JWST NIRCam) has two 2.2' x 2.2' fields of view that are capable of either imaging or spectroscopic observations. Either of two R ~ 1700 grisms with orthogonal dispersion directions can be used for slitless spectroscopy over 2.4 - 5.0 microns wavelength in each module, and shorter wavelength observations of the same fields can be obtained simultaneously. We present the latest predicted grism sensitivities, saturation limits, resolving power, and wavelength coverage performance values, based on component measurements, instrument tests, and end-to-end modeling. Operational considerations including subarray sizes, data rate limits, and simultaneous shorter wavelength observations will also be discussed. Simultaneous shorter wavelength imaging observations can be done in several filters either in-focus or defocused via weak lenses internal to NIRCam. We also discuss the possibility of simultaneous 2.4 - 5.0 micron grism and 1.0 - 2.0 micron spectroscopy using dispersed Hartmann sensors (DHSs). Both the weak lenses and DHS elements were included in NIRCam primarily for wavefront sensing purposes but have significant science applications. Finally, we illustrate potential scientific uses of the grisms by presenting simulated observations of deep extragalactic fields, galactic dark clouds, and transiting exoplanets.

9904-14, Session 3

The JWST/NIRSpec instrument: update on status and performances

Stephan M. Birkmann, European Space Agency (United States); Pierre Ferruit, European Space Agency (Netherlands); Catarina Alves de Oliveira, Torsten Böker, European Space Agency (United States); Giovanna Giardino, European Space Agency (Netherlands); Nora Lützgendorf, European Space Agency (United States); Anthony Marston, European Space Agency (Spain); Timothy Rawle, Marco Sirianni, European Space Agency (United States); Martin Stuhlinger, European Space Agency (Spain); Maurice Te Plate, European Space Agency (United States); Peter L. Jensen, Peter Rumler, European Space Agency (Netherlands); Bernhard Dorner, Max-Planck-Institut für Astronomie (Germany); Hermann Karl, Peter Mosner, Airbus Defence and Space (Germany); Ray Wright, Bay Engineering Innovations, Inc. (United States); Robert Rapp, The Hammers Co. (United States)

The Near-Infrared Spectrograph (NIRSpec) is one of the four instruments on the James Webb Space Telescope (JWST) which is scheduled for launch in 2018. NIRSpec is developed by the European Space Agency (ESA) with Airbus Defense & Space Germany as prime contractor. The instrument offers seven dispersers covering the wavelength range from 0.6 to 5.3 micron with resolutions from R~100 to ~2700. NIRSpec will be capable of obtaining spectra for more than 100 objects simultaneously using an array of micro-shutters. It also features an integral field unit with 3" x 3" field of view and a range of slits for high contrast spectroscopy of individual objects and time series observations of e.g. transiting exoplanets.

NIRSpec is in its final flight configuration and underwent cryogenic performance testing at the Goddard Space Flight Center in Winter 2015/16 as part of the Integrated Science Instrument Module (ISIM). We present the current status of the instrument and also provide an update on NIRSpec performances based on results from the ISIM level test campaign.

9904-15, Session 4

Potential large Decadal missions enabled by NASA's space launch system

H. Philip Stahl, Randall C. Hopkins, Andrew R. Schnell, NASA Marshall Space Flight Ctr. (United States); David Alan Smith, NASA Marshall Space Flight Center (United States); Angela Jackman, NASA Marshall Space Flight Ctr. (United States); Keith R. Warfield, Jet Propulsion Lab. (United States)

NASA's "Planning for the 2020 Decadal Survey" white paper calls for consideration of a Habitable Exoplanet Imaging Mission (HabEx) and a Large UV/Optical/IR Surveyor (LUVOIR) as well as Far-IR and an X-Ray Surveyor missions. NASA's Enduring Quests Daring Visions2 called for an 8- to 16-meter Large UV-Optical-IR (LUVOIR) Surveyor mission to "enable ultra-high-contrast spectroscopic studies to directly measure oxygen, water vapor and other molecules in the atmospheres of exoEarths"; and, "decode the galaxy assembly histories through detailed archeology of their present structure." And, AURA's From Cosmic Birth to Living Earths details the potential revolutionary science that could be accomplished with a 12-m class space telescope: from "directly finding habitable planets showing signs of life" to "producing transformational scientific advances in every area of astronomy and astrophysics from black hole physics to galaxy formation, from star and planet formation to the solar system."

There are many potential HabEx and LUVOIR architectures, but they are all challenged by how to affordably get a large telescope into space. JWST was severely constrained by the mass and volume capacities of its launch vehicle. This problem is solved by using the Space Launch System (SLS) with its 8 or 10 meter diameter fairings and ability to deliver 35 to 45 metric tons of payload to Sun-Earth Lagrange-2. This paper details how to the SLS's capacities fundamentally change the design rules for large space telescopes and shows how these rules can be applied to three potential mission concepts: a 4-meter monolithic off-axis telescope, an 8-meter monolithic on-axis telescope and a 12-meter segmented on-axis telescope.

9904-16, Session 4

End-to-end assessment of a large aperture segmented Ultraviolet Optical Infrared (UVOIR) Telescope architecture

Lee D. Feinberg, Norman Rioux, Matthew R. Bolcar, Alice K. C. Liu, NASA Goddard Space Flight Ctr. (United States); Olivier Guyon, The Univ. of Arizona (United States); Christopher C. Stark, Space Telescope Science Institute (United States)

Key challenges of a future large aperture, segmented Ultraviolet Optical Infrared (UVOIR) Telescope capable of performing a spectroscopic survey of hundreds of Exoplanets will be sufficient stability to achieve 10^-10 contrast measurements and sufficient throughput and sensitivity for high yield Exo-Earth spectroscopic detection. Our team has collectively assessed an optimized end to end architecture including a high throughput coronagraph capable of working with a segmented telescope, a cost-effective and heritage based stable segmented telescope, a control architecture that minimizes the amount of new technologies, and an Exo-Earth yield assessment to evaluate potential performance. These efforts are combined through integrated modeling, coronagraph evaluations, and Exo-Earth yield calculations to assess the potential performance of the selected architecture. In addition, we discusses the scalability of this architecture to larger apertures and the technological tall poles to enabling it.

9904-17, Session 4

An evolvable space telescope for future astronomical missions: 2016 update

Ronald S. Polidan, Jonathan W. Arenberg, Northrop Grumman Aerospace Systems (United States); James B. Breckinridge, Breckinridge Associates, LLC (United States); Charles F. Lillie, Lillie Consulting, LLC (United States); Howard A. MacEwen, Reviresco LLC (United States); Martin R. Flannery, Brian K. Baldauf, Northrop Grumman Aerospace Systems (United States)

In 2014 and 2015 we presented a concept for an Evolvable Space Telescope (EST) that is assembled on orbit in 3 stages, growing from a 4x12 meter telescope in Stage 1, to a 12-meter filled aperture in Stage 2, and then to a 20-meter filled aperture in Stage 3. At each "Stage" the telescope is a fully functional observatory and begins gathering science data immediately. At Stages 2, 3, and beyond, if desired, the observatory is augmented in space with additional mirror segments, structures, subsystems, and new instruments to evolve the telescope and improve performance over the years. The Evolvable Space Telescope has significantly matured since mid-2015. This paper discusses recent technical developments and future plans.

9904-18, Session 4

A technology development roadmap for a future large-aperture UV-optical-infrared space telescope

Matthew R. Bolcar, Mark Clampin, Julie A. Crooke, Lee D. Feinberg, Kate Hartman, Norman Rioux, Harley A. Thronson Jr., NASA Goddard Space Flight Ctr. (United States)

The NASA Astrophysics Division's 30-year roadmap, Enduring Quests, Daring Visions, prioritized a future large-aperture space telescope operating in the ultra-violet/optical/infrared (UVOIR) wavelength regime. The Association of Universities for Research in Astronomy (AURA) envisioned a similar observatory, the High Definition Space Telescope (HDST), in their report, From Cosmic Birth to Living Earths. Both documents outline a broad science case that combines general astrophysics with the search for biosignatures via direct-imaging and spectroscopic characterization of habitable exoplanets. We present a technology development roadmap that would enable such an observatory. Key technologies include: starlight suppression systems for high-contrast imaging; ultra-stable optical systems; precision metrology, sensing, and control systems; high-sensitivity broadband large-format detectors; and high-quality, high-throughput mirror coatings. Specific technology performance goals include 10-10 raw contrast at small inner working angles (~2?/D); wavefront error stability on the order of 10s of picometers per wavefront control step; autonomous on-board sensing and control; single-photon detectors spanning the UVOIR band; and low-polarization mirror coatings that enable high-throughput from below 100 nm through the near-infrared. These technologies will enable significant advances over current and planned observatories in terms of sensitivity, angular resolution, stability, and high-contrast imaging. We review the potential science goals of a large UVOIR observatory and outline the top-level telescope and instrument performance requirements. We define the required technology capabilities, current state-of-the-art performance, and current Technology Readiness Level (TRL), thus identifying the current technology gaps. Current, planned, and recommended technology development efforts are also reported.

9904-87, Session PS1

Coatings induced phase shift and impact on Euclid imaging performance

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Euclid is an European Space Agency mission to map the geometry of the dark Universe. The mission will investigate the distance-redshift relationship and the evolution of cosmic structures. It achieves this by measuring shapes and redshifts of galaxies and clusters of galaxies out to redshifts ~2, or equivalently to a look 10 billion years back in time. Euclid makes use of two cosmological probes, in a wide survey over the full extragalactic sky. One is based on the the Weak Gravitational Lensing (WL) and the other is the Baryonic Acoustic Oscillations (BAOs). Each probe has a dedicated instrument working, each working in a specific spectral range: the visible range (500 nm to 900nm) for the WL probe and the near-infra-red (920 nm to 2000nm) for the BAO probe. The light is spectrall separated by a dichroic reflecting the visible part of the light. The WL is a method to map the dark matter and measure dark energy by measuring the distortions of galaxy images by mass inhomogeneities along the line-of-sight. This probe requires extreme image quality thus constraining the optical system wavefront error.

The challenging constraints imposed on the telescope imaging performances have driven the design, manufacturing and characterisation of the multi-layered coatings of the dichroic. Indeed the coatings inhomoeneities will introduce a wavelength dependent phase-shift resulting in PSF changes. Such changes must be characterized and/or simulated since they could be non-negligible contributors to the scientific performance accuracy. Several papers on this topic can be found in litterature, however the results can not be applied directly to Euclid's dichroic coatings. In particular an applicable model of the phase-shift variation with the wavelength could not be found and needed to be developped. We will present in this paper the outcomes of the work performed for the characterization and modelisation of the dichroic wavefront in reflection for any wavelenght.

9904-88, Session PS1

The Euclid VIS focal plane assembly STM: from the integration to the qualification tests

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In the frame work of the ESA Euclid mission to be launched in 2020, the Euclid Consortium is developing an extremely large and stable focal plane for the VIS instrument. After an extensive phase of definition and study over 4 years made at CEA on the thermo-mechanical architecture of that Focal Plane, the first model (Structural and Thermal Model) has been assembled and qualified.

The VIS Focal Plane Assembly integrates 36 CCDs (operated at 150K) connected to their front end electronics (operated at 280K). This Focal Plane will be the largest focal plane (?0.6 billion pixels) ever built for space application after the GAIA one. The CCDs are CCD273 type specially designed and provided by the e2v company under ESA contract, front end electronics is studied and provided by MSSL.

The Thermal and Structural Model is fully representative of the Flight Model regarding the thermo-mechanical architecture. As the instrument development philosophy follows a Proto Flight approach this choice has been made very early in the development program in order to reduce the risk on the PFM program. So the AIT/AIV plan has been built in order to fully validate since the STM program the overall integration, verification and qualification sequences, taking into account the very stringent cleanliness requirement. The FPA STM integrates 36 CCDs representative of the flight model except for the detection function. Electrical configuration of the front end electronics provides electrical interface in order to power the CCDs and check integrity of all the electrical links to CCDs.

In this paper we first recall the architecture of the VIS-FPA and especially the solutions proposed to cope with the scientific needs of an extremely stable focal plane, both mechanically and thermally leading to a SiC structure. The modular architecture concept, considered as a key driver for such big and complex focal plane is detailed. Parallel to that, the integration workflow including verification steps is fully depicted including specific aspects linked to the use of SiC. Validation and qualification test program is described. A summary of geometrical measurements, thermal balance tests and vibrations tests including the main Ground Support Equipment description are reported.

9904-89, Session PS1

The Euclid/VIS shutter unit

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The VIS instrument on-board the Euclid mission will feature a shutter unit (RSU), which main function is to prevent direct light from falling onto the instrument CCDs when the latter are flushed between one scientific exposure and the next. The RSU permits at the same time to keep the fine guidance sensors of the instrument to be exposed to light continuously, in order to maintain the required instrument pointing accuracy and stability. The RSU will be operating at cryogenic temperatures (110-160 K) and planned to perform about a milion of opening/closing cycles.

The engineering model of the RSU has been already manufactured and tested, while the structural thermal model is under assembly and will be tested in the early 2016. The RSU flight model will be completed in 2017.

In this contribution we provide an overview of the consolidated RSU design, following the completion of the final detailed design phase, and summarize the remaining development stages.

9904-90, Session PS1

The power and mechanism control unit of the VIS instrument for the Euclid space mission

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EUCLID is a European Space Agency (ESA) scientific space borne mission designed to map the geometry of the dark universe. The satellite will be equipped with a 1.2m telescope and two instruments on-board: a high quality visible imager (VIS) and a near-infrared spectrometer and photometer (NISP). The VIS instrument is composed of different subsystems: the Focal Plane Assembly (FPA), a 36 CCD focal plane in charge of the detection of visible light for imaging, the Readout Shutter Unit (RSU) to close the optical path during focal plane readout and for dark calibration, the Calibration Unit (CU) to illuminate the FPA with flat field for calibration, all being located in the satellite payload module and other subsystems, located in the service module, the Command and Data Processing Unit (CDPU) to control the whole instrument, perform data processing and interface with the spacecraft for data handling and the Power and Mechanism Control Unit (PMCU) to control the RSU, CU and monitor FPA temperature.

The PMCU is under the responsibility of the French Atomic Energy Commission (CEA), with support of the French space agency CNES. This unit receives high-level commands from the CDPU and processes it by controlling with a high degree of autonomy the CU and the RSU. It performs as well the acquisition of a large number of analogue housekeeping parameters of the three payload located VIS subsystems for both real time monitoring by CDPU software and on-ground monitoring and analysis.

The precision and the repeatability of the motion of the RSU, and consequently of control performed by the PMCU, have a direct impact on the science since they define the detector exact exposure time. Moreover the motion profile is defined to limit parasitic vibrations that may affect the very accurate pointing system of the satellite. In the same manner the CU subsystem requires to the PMCU to drive multiple wavelength LED-based calibration sources with a high stability all along the mission.

In this paper, we will present the design of the PMCU that of been defined to fulfil the requirement specifications and higher-level requirements such as reliability, failure mode and radiation mitigation. We will as well present results of functional and early performance tests performed on the EM model of the unit.

9904-92, Session PS1

Detailed design and first tests of the application software for the instrument control unit of Euclid-NISP

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In this paper we describe the detailed design of the application software (ASW) of the instrument control unit (ICU) of NISP, the Near-Infrared Spectro-Photometer of the Euclid mission. This software is based on a

real-time operating system (RTEMS) and will interface with all the subunits of NISP, as well as the command and data management unit (CDMU) of the spacecraft for telecommand and housekeeping management. We briefly review the main requirements driving the design and the architecture of the software that is approaching the Critical Design Review level.

The interaction with the data processing unit (DPU), which is the intelligent subunit controlling the detector system, is described in detail, as well as the concept for the implementation of the failure detection, isolation and recovery (FDIR) algorithms.

The first version of the software is under development on a Breadboard model produced by AIRBUS/CRISA. We describe the results of the tests and the main performances and budgets.

9904-93, Session PS1

Modeling effects of common molecular contaminants on the Euclid infrared detectors

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Cleanliness specifications determine the level of particulates and areal density of molecular contaminant on surfaces. The chemical composition of these contaminants is not specified beyond the density. Here we use a toy model antireflection coating fit to the measurements of prototype infrared detector arrays to assess the impact on detector quantum efficiency of contaminant thickness and type. Provided that the contaminant does not react with the detector surface, layers at thickness meeting typical specifications, ~1microgram/cm2, have a negligible effect on the detector quantum efficiency.

9904-94, Session PS1

A comprehensive stray-light analysis of the Euclid NISP instrument

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An ASAP analysis has been conducted for the CDR of the EUCLID-NISP near infra-red instrument. The results are presented and compared to analytical estimates as well as to a previously published ZEMAX study. In order to have a profound basis for our dust modelling we compare the model parameters to measurements of actual lenses that where pre-contaminated (and cleaned again) in our facilities.

Special attention is drawn on the modelling of structural parts, as well as on the baffling structures. Complex light paths are identified along the mechanics to show the depth of analysis that is possible in such a study.

9904-95, Session PS1

How to test NISP instrument for Euclid mission in laboratory

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The ESA mission Euclid is designed to explore the dark side of the Universe and to understand the nature of the dark energy responsible of the accelerating expansion of the Universe. Its objective is to map the geometry of the dark Universe by investigating the distance-redshift relationship and the evolution of cosmic structures. The NISP (Near Infrared Spectro-Photometer) is one of the two Euclid instruments operating in the near-IR spectral region (0.9-2?m). NISP will be fully integrated and tested at Laboratory d'Astrophysique de Marseille (LAM). In particular, NISP flight model (FM) has to be tested under vacuum and thermal conditions respectively in order to qualify the instrument in its operating environment and to perform the final acceptance test before delivery to the payload. The test campaign will regroup functional tests of the detectors and wheels, performance tests of the instrument, calibration procedure validation and observations scenario test, all done at LAM. One of the main objectives of the test campaign will be the measurement of the focus position of NISP with respect to the EUCLID object plane. In order to achieve these tests campaign, a global Ground Support Equipment (GSE) called the Verification Ground System (VGS) has to be developed. The VGS will be a complex set of GSE, developed by LAM and its partners, to fulfil all the requirements of the test campaign. All the VGS parts will be integrated into ERIOS chamber. The VGS is made of: a telescope simulator to simulate the EUCLID telescope and to inject light into NISP for optical performance tests, a thermal environment to be used for NISP thermal balance and verification, a sets of mechanical interfaces to align and install all the parts into ERIOS chamber, the NISP Electrical GSE (EGSE) to control the instrument during the test and a metrology system to measure

the positions of the components during the test. We will present the preliminary design and concepts chosen for the NISP test configuration, in particular the trade-off made for the design of the thermal and mechanical GSE and the foreseen configuration for the test into ERIOS. In particular we will show the main difficulties we have to deal with: design of thermal environment at 95K with 4mK stability, the development of a metrology system in vacuum, knowledge of the focus position within 150µm in cold, etc. The main objectives of the NISP test will be explained and how the VGS responds to the test requirement. In addition, we will underline the challenges that represent such an important and long test of NISP FM and how this test campaign is foreseen.

9904-96, Session PS1

Focal plane mechanical design of the NISP/Euclid instrument

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Currently in phase C, the Euclid mission selected by ESA in the Cosmic Vision program is dedicated to understand dark energy and dark matter. NISP (standing for Near Infrared Spectro-Photometer) is one of the two instruments of the mission. NISP will combine a photometer and a spectrometer working in the near-IR (0.9-2 microns). Its detection subsystem (called NI-DS) is based on a mosaic of 16 IR detectors cooled down to 90K which are supported by a molybdenum plate. The front-end readout electronics (working at 130K) are supported by another structure in Aluminum. The NI-DS is mounted on NISP main structure thanks to a panel in Silicon Carbide (SiC). Finally an optical baffle in Titanium will prevent the rogue light to reach the detectors.

On top of the complexity due to the wide range of temperatures and the various materials imposed at the interfaces; the NI-DS has also to incorporate an internal adjustment capability of the position of the focal plane in tip/tilt and focus.

This article will present the detailled design of the detection system of NISP and its development status. In particular, it will describe the complete breadboard model which has been developed and tested at Laboratoire d'Astrophyique de Marseille (LAM).

9904-97, Session PS1

EGSE customization for the Euclid NISP instrument AIV/AIT activities

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The Near Infrared Spectro-Photometer (NISP) on board the Euclid ESA mission will be developed and tested at various levels of integration using various test equipment. The Electrical Ground Support Equipment (EGSE) shall be required to support the assembly, integration, verification and testing (AIV/AIT) and calibration activities at instrument level before delivery to ESA, and at satellite level, when the NISP instrument is mounted on the spacecraft. In the case of the Euclid mission this EGSE will be provided by ESA to NISP team, in the HW/SW framework called "CCS Lite", with a possible first usage already during the Warm Electronics (WE) AIV/AIT activities. In this paper we discuss how we will customize that "CCS Lite" as required to support both the WE and Instrument test activities. This customization will primarily involve building the NISP Mission Information Base (the CCS MIB tables) by gathering the relevant data from the instrument sub-units and validating these inputs through specific tools. Secondarily, it will imply developing a suitable set of test sequences, using uTOPE (an extension to the TCL scripting language, included in the CCS framework), in order to implement the foreseen test procedures. In addition and in parallel, custom interfaces shall be set up between the CCS and the NI-IWS (the NISP Instrument Workstation, which will be in use at any level starting from the WE activities), and also between the CCS and the TCC (the Telescope Control and command Computer, to be only and specifically used during the instrument level tests).

9904-98, Session PS2

Quantum efficiency measurement of the Transiting Exoplanet Survey Satellite (TESS) CCD detectors

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The Transiting Exoplanet Survey Satellite (TESS) will search for planets transiting bright stars with Ic ? 13. TESS has been selected by NASA for launch in 2017 as an Astrophysics Explorer mission and is expected to discover a thousand or more planets that are smaller in size than Neptune, including dozens of Earth-sized planets. TESS will employ four wide-field optical charge-coupled device (CCD) cameras with a band-pass of 600 nm – 1000 nm to detect temporary drops in brightness of stars due to planetary transits. The 1000 nm limit is set by the quantum efficiency of the CCDs. The detector assembly consists of four back-illuminated MIT Lincoln Laboratory CCID-80 devices. Each CCID-80 device consists of 2048x2048 imaging array and 2048x2048 frame store regions, with 15x15 ?m pixels. The 2x2 array of CCDs is contained within 62x62 mm area with a 2 mm gap between the CCDs.

Very precise on-ground calibration and characterization of CCD detectors will significantly assist in the analysis of the science data obtained in space. The characterization of absolute quantum efficiency of the CCD detectors is a crucial part of the characterization process because it will hugely aid in data analysis of the mission. Quantum efficiency affects the performance of the CCD when working at very low light levels. An accurate optical test bench with very high photometric stability has been developed to perform precise measurements of the absolute quantum efficiency. The setup consists of a vacuum dewar with a single CCID-80 device mounted on a cold plate that is maintained at the operating temperature of -75? to reduce the dark current to a negligible level. A calibrated reference photodiode is mounted next to the CCD and maintained at the calibration temperature of 25?. The CCD electronics package consists of two compact printed circuit boards that are located beneath the cold plate. Eleven band-pass filters over the range of 575 nm – 1075 nm with 50 nm bandwidth are used for wavelength selection. A very stable laser-driven light source is integrated with a closed-loop intensity stabilization unit to control variations of the light source down to a few parts-per-million when averaged over 60 s. The stabilization unit is a patented development by the CHaracterising ExOPlanet Satellite (CHEOPS) team at the University of Geneva. Light from the stabilization unit enters a 20 inch integrating sphere. The output light from the sphere produces near-uniform illumination on the cold CCD and on the calibrated reference photodiode inside the dewar. The ratio of the CCD and photodiode signals provides the absolute quantum efficiency measurement. The design, key features, noise and error analysis, and results from the test campaign are presented. Future work involving precision flat-field calibration of single CCDs using the same setup is also discussed.

9904-99, Session PS2

Photometric testing of the TESS engineering camera

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The Transiting Exoplanet Survey Satellite (TESS) is scheduled for launch in 2017 by NASA's Explorers Program. TESS will conduct an all-sky survey during its 2-year mission using four optical cameras to find transiting planets around dwarf stars in the solar neighborhood. In order to demonstrate the photometric precision that is required to detect Earths and Super-Earths, an engineering camera with flight like design and functionality was built. We have constructed a test bed for testing this camera that consists of a thermal vacuum chamber which cools the entire camera to its operating temperature of -75C, and an optical bench containing a highly collimated system which projects point sources (a target star and multiple guide stars) from a fiber head. The camera is held inside the chamber by a cradle that coarsely yaws and rolls the instrument on its axes, allowing projection of the target and guide stars anywhere on the focal plane. The fiber head is mounted on an xy picomotor stage, providing fine motion which translates the star images on the focal plane with sub-pixel resolution. The laser driven light source is wide band and highly stable. The output is split between the target and the guide stars, and is filtered for desired wavelengths and attenuated for appropriate intensity. The guide stars are used to cancel out thermo-mechanical motion caused by the cooling cycles via a closed loop feedback to the xy stage. Jitter motion can be added to determine its effect on the photometric precision. The target star is fixed to the same pixels for more than two weeks mimicking an orbital period, to evaluate the photometric precision. Transits are simulated to depths of <100 ppm, using a controlled shutter.

9904-100, Session PS2

The testing and characterization of TESS CCDs

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The Transiting Exoplanet Survey Satellite (TESS) is an Explorer-class mission dedicated to finding planets around bright, nearby stars so that more detailed follow-up studies can be done. TESS is due to launch is 2017 and careful characterization of the detectors will need to be completed on ground before then to ensure that the cameras will be within their photometric requirement of <60ppm. TESS will fly MIT-Lincoln Laboratories CCID80s as the main scientific detector for its four cameras. They are 100-micron deep depletion devices which have low dark current noise levels, enough so that they can operate at low light levels at room temperature. They also each have a frame store region, which reduces smearing during readout and allows for near continuous integration. This paper describes the methodology and hardware that are being developed for testing individual CCID80s with optical and X-ray illumination. In order to determine accurate linearity, an LED system that generates a programmable series of pulses is used. The same system is employed to establish the gain at high signal levels (up through full well), while 55Fe and 109Cd X-ray sources are used at low signal levels. The gain dependence on thermal variation over the operational range is measured. Finally, the CCID80 has a charge injection register that is used to determine the upper limit of the charge transfer inefficiency.

9904-101, Session PS2

The instrument control unit of the ESA-PLATO 2.0 mission

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PLATO 2.0 has been selected by ESA as the third medium-class Mission (M3) of the Cosmic Vision Program, to be launched in 2024. Its Payload is conceived for the study of planetary system formation and evolution and to answer fundamental questions concerning the existence of other planetary systems like our own, including the presence of potentially habitable new worlds.

It is composed of 34 small telescopes whose fields of view will cover more than 2200 square degrees. The telescopes are split into two groups of 32 and 2 units. The latter will provide the capability to observe bright targets and are dubbed fast telescopes. Combined with the 32 (normal) telescopes, the whole set will make it possible to attain a large photometric visible magnitude range, from ~4 to ~16.

Focusing on a subset of brighter targets (mv 4-11), the PLATO Payload will be able to detect and characterise planets down to Earth size by means of photometric transits, with their masses determined through ground-based radial velocity follow-up measurements. Moreover, given the brightness of this subset of samples, PLATO will extensively perform asteroseismology on these targets to obtain highly accurate stellar parameters as masses, radii and ages allowing for a precise characterisation of planetary bulk parameters.

The adoption of an observing program including two long pointing of 2-3 years each, will provide the capability to observe planets down to the habitable zone of solar-like stars with a first basic assessment of the main characteristics of their atmospheres, opening the way to future space missions designed to perform spectroscopy of these targets.

The main scientific requirement to detect and characterise a large number of terrestrial planets around bright stars plays a key role in defining the PLATO observing strategy and its own Payload.

In particular, the 4 CCDs per focal plane, for a total of 136 CCDs, pose strong constraints on the readout and the subsequent processing of a huge set of data, which requires then a customised Data Processing System (DPS).

The DPS is composed of 16 Normal DPUs (Data Processing Units) and 2 Fast DPUs (one per each Fast camera/telescope) designed to pre-process

the downloaded images and to extract the photometric signal from the selected targets as well as to select a reduced sample of imagettes around a subset of stellar targets. The DPUs will also be in charge of the detection and removal of outliers from the photometric signals. All the scientific data and payload housekeepings will be collected by an Instrument Control Unit (ICU) acting as the main interface between the Payload and the spacecraft. The PLATO 2.0 ICU will be in charge of data collection from DPS and pre-processing, data compression, managing of the Payload SpaceWire network and received telecommands, telemetry formatting towards the SC. It is conceived as a full cold-redundant unit implementing a minimal cross-strapping to improve the DPS reliability.

This paper gives an overview of the overall PLATO 2.0 DPS, mainly focusing on the architecture and processing capabilities of the ICU.

9904-102, Session PS2

Manufacturing and alignment tolerance analysis through Montecarlo approach for PLATO

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The project PLAnetary Transits and Oscillations of stars (PLATO) is one of the selected medium class (M class) missions in the framework of the ESA Cosmic Vision 2015-2025 program. The main scientific goal of PLATO is the discovery and study of extrasolar planetary systems by means of planetary transits detection.

According to the current baseline, the scientific payload consists of 34 all refractive telescopes having small aperture (120mm) and wide field of view (diameter greater than 37 degrees) observing over 0.5-1 micron wavelength band. The telescopes are mounted on a common optical bench and are divided in four families of eight telescopes with an overlapping line-of-sight in order to maximize the science return. Remaining two telescopes will be dedicated to support on-board star-tracking system and will be specialized on two different photometric bands for science purposes.

The performance requirement, adopted as merit function during the analysis, is specified as 90% enclosed energy contained in a square having size 2 pixels over the whole field of view with a depth of focus of +/-20 micron. Given the complexity of the system, we have followed a Montecarlo analysis approach for manufacturing and alignment tolerances. We will describe here the tolerance method and the preliminary results, speculating on the assumed risks and expected performances.

9904-103, Session PS2

Radiation, thermal gradient, and weight: a threefold dilemma for PLATO

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The opto mechanical subsystem of the payload is made of 34 normal telescope optical units (N-TOUs) ad 2 fast telescope optical units (F-TOUs). The optical configuration of each TOUs is an all refractive design based on six properly optimized lenses. In the current baseline, in front of each TOUs a Suprasil window is foreseen. The main purposes of the entrance window is to shield the following lenses from possible damaging high energy radiation and to mitigate the thermal gradient that the first optical element will experience during the launch from ground to space environment. In contrast, the presence of the window increases the overall mass by a non-negligible quantity. We describe here the radiation and thermal analysis and their impact on the quality and risks assessment, summarizing the trade-off process with pro and cons on having or dropping the entrance window in the optical train.

9904-104, Session PS2

Thermal effects on PLATO point spread function

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The PLAnetary Transits and Oscillations of stars (PLATO) space mission primary science goal is to detect and characterise exoplanets around bright solar-type stars. The PLATO instrument consists of 32 telescopes with an aperture of 12 cm and will provide a 48.5o x 48.5o field of view (FoV). To achieve its science goals, PLATO will need to provide measurements of the magnitude of the target stars with an accuracy of a few tens part per million (ppm). To this end, the instrument stability is a major issue in the instrument design.

Here we propose a concept study aiming at analysing thermal effects in PLATO in terms of overall temperature, longitudinal and lateral gradients.

We characterise these effects by evaluating the PSF centroids shift and

the Enclosed Energy variations across the whole FoV. These patterns can then be used to gauge the thermal behaviour of each individual telescope in order to improve the local photometric calibration across the PLATO FoV. This is going to be compared in our study with respect to the most conventional photometry flat fielding taking in both cases advantages of the large number of continuously monitored stars (up to a hundred million).

9904-105, Session PS2

A display model for the TOU of PLATO: just a cool toy or a cluster of opportunities?

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We produced a "toy-model" of one Telescope Optical Unit of PLATO, the Medium sized mission selected by ESA to fly in 2024. This is a six lenses dioptric very wide field camera with a window in front to take care of radiation impact on the first lens whose optical glass cannot be replaced with a radiation hardened one. The main aim of this project

is just to produce a "cool" model for display purposes, in which one can

"explore" the details of the inside through some openings in the tube, in order to visually inspect some of the fine details of the opto-mechanics. While its didactic and advertising role is out of doubt, during its construction we realized that some interesting outcome can be of some relevance for the project itself and that some findings could be useful, in order to assess the ability of producing with the same technology some (of course of much more modest quality) optical systems. In this context, we immediately dropped the option of producing the lenses with opaque material painted with a color resembling a refractive material (like blue for instance) and decided

to actually produce them with transparent plastic. Furthermore the surfaces are then finely polished in order to give them basic optical properties. Such an optical system has only very coarsely the converging

properties of the original nominal design for a number of reasons: the refractive indexes are not the nominal ones, the quality of the surfaces and their nominal values are only roughly, within a few percent, the targeted one, and the way the surfaces are built up makes them prone to some diffraction effects. However, the bulk of the lens and the surface roughness will give a large magnification of the scattering effects that will be experienced, at a much lower level, on the actual flight model. We investigated through propagation of a laser beam and by digital camera the main stray light modes that this toy-model offers. In other words, the model amplifies, to a large extent, the negative bulk scattering and spurious reflection just because surfaces and materials are orders of magnitude rougher that the intended one. Even if this did not allow to attempt to make any quantitative measurement, in order to scale down to the actual one, we used it to look out independently for the main sources of stray light and we compared them with the one discussed by the optical design team, obtained using professional ray tracing code.Finally, we point out some of the technicalities used in the design to mimic the finest mechanical elements that cannot be safely incorporate in the final design and to produce pieces of size much larger than the maximum volume allowed by our 3D printer in a single shot.

9904-106, Session PS2

An integrated payload design for the Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL)

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ARIEL (the Atmospheric Remote-sensing Infrared Exoplanet Large-survey) is one of the three candidates for the next ESA medium-class science mission (M4) expected to be launched in 2026. This mission will be devoted to observing spectroscopically in the infrared a large population of warm and hot transiting exoplanets (temperatures from ~500 K to ~3000 K) in our nearby Galactic neighbourhood, opening a new discovery space in the field of extrasolar planets and enabling the understanding of the physics and chemistry of these far away worlds. The three candidate missions for M4 are now in a Phase A study which will run until mid-2017 at which point one mission will be selected for implementation.

ARIEL is based on a 1-m class telescope feeding both a moderate resolution spectrometer covering the wavelengths from 1.95 to 7.8 microns, and a four channel photometer (which also acts as a Fine Guidance Sensor) with bands between 0.55 and 1.65 microns. During its 3.5 years of operation from an L2 orbit, ARIEL will continuously observe exoplanets transiting their host star.

This paper presents the overall view of the integrated design of the payload which is proposed for this mission. It tightly integrates the various payload elements in order to allow the exacting photometric stability targets to be met while providing simultaneous spectral and photometric data from the visible to the mid-infrared. We identify and discuss the key requirements and technical challenges for the payload and address the trade-offs that we are undertaking. We will show how we will produce a fully integrated and calibrated payload for ARIEL that can be built within the mission and programmatic constraints and will meet the challenging scientific performance required for transit spectroscopy.

9904-107, Session PS2

Design of an afocal telescope for the ARIEL mission

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ARIEL (the Atmospheric Remote-sensing Infrared Exoplanet Large-survey) is one of the three candidates for the next ESA medium-class science mission (M4) expected to be launched in 2026. This mission will be devoted to observing spectroscopically in the infrared (IR) a large population of known transiting planets in our Galaxy, opening a new discovery space in the field of extrasolar planets and enabling the understanding of the physics and chemistry of these far away worlds.

ARIEL is based on a 1-m class telescope ahead of two spectrometer channels covering the band 1.95 to 7.8 microns. In addition there are two photometric channels: one in the visible and one in the near-IR, to monitor the stellar activity, measure the albedo and detect clouds. During its 3.5 years operations from L2 orbit, ARIEL will continuously observe exoplanets transiting their host star.

The ARIEL design is conceived as a fore-module common afocal telescope that will feed the spectrometer and photometric channels. The telescope optical design is an off-axis portion of a two-mirror classical telescope coupled to a tertiary off-axis paraboloidal mirror collimating the output beam.

The telescope and optical bench operating temperatures, as well as that of some subsystems, will be monitored and fine tuned/stabilised mainly by means of a thermal control subsystem (TCU- Telescope Control Unit) working in feedback closed-loop and hosted by the main Payload electronics unit, the Instrument Control Unit (ICU). In particular, one of the main functions of the TCU will be to switch on/off the Payload decontamination heaters when operating the instrument in Decontamination Mode, during the Commissioning Phase and cyclically, if required.

The TCU will be also in charge of controlling the Refocusing Mirror (M2) mechanism and the Fine Steering tip/tilt Mirror (M4) mechanism thanks to proper electronic driver sections.

In this paper the telescope requirements will be given together with the foreseen design. The technical solution chosen to passively cool the telescope unit will be detailed discussed.

9904-108, Session PS2

AIRS: the infrared spectrometer of the ARIEL space mission

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ARIEL (the Atmospheric Remote-sensing Infrared Exoplanet Large-survey) is one of the three candidates for the next ESA medium-class science mission (M4) scheduled for launching in 2026. The three candidate missions for M4 are now in a Phase A study which will run until mid-2017 at which point one mission will be selected for implementation.

ARIEL is a 3.5 years spectroscopic survey in the infrared of a population of hundredth of warm and hot (temperatures from ~500 K to ~3000 K) transiting gas giants, Neptunes and super-Earths planets around a range of host star in our nearby Galactic neighbourhood. We target planets hotter than 500K to take advantage of their well-mixed atmospheres which should show minimal condensation and sequestration of high-Z materials and thus reveal their bulk and elemental composition (especially C, O, N, S, Si).

ARIEL will explore the nature of exoplanet atmospheres and interiors and, through this, the key factors affecting the formation and evolution of planetary systems.

ARIEL is a 1-m class telescope on L2 orbit carrying a single, highly capable and stable spectrometer (named AIRS) covering 1.95 – 7.80 ?m with a resolving power of 200. It is mounted on a single optical bench with a Fine Guidance Sensor (FGS) that provides closed-loop feedback to the high stability pointing of the spacecraft. The FGS provides simultaneous information on the photometric stability of the target stars in 4 broad bands between 0.55 and 1.65 microns. The instrument design uses only technologies with a high degree of technical maturity.

We will present in details the concept of the AIRS spectrometer. AIRS is a single module that incorporates two channels separated by a dichroic filter covering the 1.95-3.9 ?m and 3.9-7.8 ?m ranges, respectively. The preliminary design of the spectrometer consists mainly of separate optics and grating for each of the wavelength channels integrating the full wavelength range onto a single detector. The optical design is kept simple with the minimal number of components and without any mechanisms, thus providing many advantages in terms of compact and lightweight instrument architecture. The baseline detectors actively cooled to a temperature of 35K are the Teledyne MCT arrays developed for NEOCAM, but we are also studying alternatives with European manufacturers, Seles-eS, AIM and CEA/LETI development programs. We wil discuss the performance of AIRS.

9904-109, Session PS2

The Atmospheric Remote-sensing Infrared Exoplanets Large-survey (ARIEL) payload electronic subsystems

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The ARIEL mission has been proposed to ESA by an European Consortium as the first space mission to extensively perform remote-sensing on the atmospheres of a well defined set of warm and hot transiting exoplanets, with temperatures ranging between ~600 K and ~3000 K. ARIEL will observe a large number (~500) of gas giants, Neptunes and super-Earths around a variety of host star types exploiting transit spectroscopy in the ~2-8 ?m spectral range and broad-band optical photometry. It will target planets hotter than 600 K to take advantage of their well-mixed atmospheres, which should show minimal condensation and sequestration of heavy materials, revealing their bulk properties. ARIEL will also address habitable planets, albeit not directly. Instead, this will follow from its capability to detect the presence of atmospheres on many terrestrial planets outside the habitable zone and, in many cases, characterise them.

This will represent a fundamental breakthrough in understanding the physical and chemical processes of a large sample of exo-atmospheres and to probe in-space technology for the next generation of dedicated space-based observatories, able to detect and characterise Earth analogues.

ARIEL has been proposed as a medium-class mission competing for the M4 ESA launch opportunity in the context of the Cosmic Vision program. Thanks to the heritage from previous studies on similar space instrumentation, its overall payload and electronics subsystems are designed to fully comply with the limitations imposed by the constraints of the ESA call. In particular, the payload electronics subsystems will aim at a full integration and simplification, respecting mass, power, volume and thermal budgets and guaranteeing the fulfilment of the science requirements. The ARIEL electronics subsystems shall mainly drive and control the telescope mirrors actuators, the mirrors temperatures when operated in decontamination mode, the IR calibration source as well as interfacing the spectrometer detectors Cold Front End Electronics (CFEEs), collecting and processing the produced data and managing the guidance sensor. A dedicated unit acting as FGS (Fine Guidance Sensor) is foreseen to guarantee the spacecraft attitude and the fine pointing on the selected target along with an Instrument Control Unit as the main payload electrical interface to the detectors CFEEs and the spacecraft. The ICU is designed as a highly integrated subsystem able to host and to perform the main functions required to interface the spectrometer cold-end, to perform data processing and to fully control the overall payload. It shall manage the payload operational modes, the received commands from the spacecraft and format the science telemetry towards the satellite mass memory, once properly compressed. ICU will be a fully cold redundant unit with a minimal internal cross-strapping, improving its own reliability.

This paper will provide an overview on the ARIEL payload electronics subsystems, showing the main choices leading to a compliant design with respect to the ESA foreseen budgets.

9904-111, Session PS2

Dimensional stability testing in thermal vacuum of the CHEOPS optical telescope assembly

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In October 2012 CHEOPS was selected as the first S-class mission in the ESA Cosmic Vision program 2015-2025. This mission is executed as a partnership between Switzerland and ESA's Science Programme, with important contributions from Austria, Belgium, France, Germany, Hungary, Italy, Portugal, Spain, Sweden, and the United Kingdom. Here the university of Bern is responsible for the optical instrument and the OTA itself is constructed by Almatech. Launch readiness is foreseen for 2017.

The CHEOPS telescope is a 32cm diameter (30cm clear aperture)on-axis Ritchey-Chrétien telescope. Zerodur mirror are positioned in a CFRP structure, in combination with a kinematic mounting the assembly is integrated on the thermally isolated optical bench. Main goal here is to achieve the dimensional stability required for the scientific operation, where a distinction is made between the in-orbit stability case and the settling-stability case. For the settling deformations between the telescope mirrors are allowed of up to ~5µm and ~20µRad whereas the in orbit stability requires deformations to be smaller than 0.75µm and 5µRad. Requirements on the metrology setup are even more stringent than this.

TNO has designed, commissioned and validated a test setup for this experiment making use of the in-house expertise and facilities. The overall thermal vacuum testing was split in thermal vacuum cycling and the stability test, the main difference being that the length metrology system was not included in the thermal cycling. All thermal vacuum tests are performed in TNO's VCF facility inDelft. For the thermal cycling test a simple test interface was used and no thermal insulation was applied to increase the radiative transfer between the test facility and test object. For the stability tests the OTA is accurately aligned using a theodolite and integrated on a metrology frame equipped with three interferometers. The laser source and detectors are placed outside the vacuum facility. An active beam alignment system is implemented to preserve the beam alignment on the test object, compensating for facility deformation during the thermal vacuum test. This approach allows nm-level monitoring of length changes between the dummy mirrors in the OTA over three different paths. These three measurements are converted to deformations between the mirrors. During the latter experiment thermal insulation is added around the OTA to assure the thermal stability and homogeneity of the OTA during testing. In the experiments on the STM2, it is demonstrated that all stability requirements are met. Based on the results of these experiments the STM is upgraded to the FM.

This paper describes operation of the test facilities as well as the validation of its performance during qualification experiment. It describes the implementation of the metrology inserts on the test object and concludes with the achieved overall performance of the CHEOPS OTA itself.

9904-112, Session PS2

The performance of the CHEOPS calibration bench

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The CHaracterising ExOPlanet Satellite (CHEOPS) is a photometric transits mission aimed a characterizing already known exoplanets. By being able to point at nearly any location on the sky, it will provide the unique capability of determining accurate radii for a subset of those planets for which the mass has already been estimated from ground-based spectroscopic surveys. To reach its goals CHEOPS will measure photometric signals with a precision of 20 ppm in 6 hours of integration time for a 9th magnitude star.

Achieving the precision goal requires thorough post-processing of the data acquired by CHEOPS to remove the instrument's signature. To this purpose, a rigorous calibration campaign will be conducted before launch order to measure its behavior under the different environmental conditions.

The main tool of this calibration campaign is a purpose-built calibration system that will inject a stimulus beam in the CHEOPS and measure its response to the variation of electrical and environmental parameters. Ultimately, the CIS photometric performance will be measured on an artificial star, applying the correction model.

The design of this calibration system has been presented previously In this paper we want to address the actual performance of this bench and how we have validated it before mating it with CHEOPS. Light stabilization, field tracking, pupil tracking, beam shifts, all major contributor to the photometric budget have been characterized separately.

9904-113, Session PS2

Aligning the demonstration model of CHEOPS

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CHEOPS (CHaracterizing ExOPlantes Satellite) is an ESA Small Mission, planned to be launched at the end of 2017. It will be sent into a low Earth (650-800 km) sun-synchronous orbit with the main goal to perform, through photometry, precise characterization of radii of exo-planets orbiting bright stars (V<12) bright stars already known to host planets.

It is a Ritchey-Chretien two mirrors centered telescope with an aperture of 320 mm followed by a Back End Optics (BEO) whose main purposes are to re-image the telescope focal plane on the detector, to provide an intermediate pupil to place a mask for the straylight rejection and to reshape a defocused PSF accordingly to specifications. It will provide a FoV with a diameter of 0.32 degrees.

As for every space mission, the development of intermediate models is highly important in order to decrease all possible risks. In particular, being CHEOPS also a fast-track mission, it is of paramount importance to demonstrate the feasibility and the reliability of the AIV procedures, as well as the development of adequate GSEs, ahead of their implementation on the Flight Model.

For this reason, in collaboration with the University of Bern and the Italian Prime Contractor, SELEX ES, a Demonstration Model of CHEOPS telescope was developed. It consists in a non-flying CHEOPS model whose mechanics is fully representative concerning interfaces but not thermally equivalent (it is realized in aluminum), and whose optics exhibits optical quality and handling capabilities almost identical to the flight model, allowing to test procedures for handling, integration, alignment and characterization, with accent on the optical viewpoint.

In this paper we describe the work performed at the laboratories of INAF Padova, where the CHEOPS Demonstration Model was assembled, aligned and tested in ambient temperature, with emphasis on the verification of the uncertainty in the optical quality measurements introduced by the starlight simulator and the way the alignment and optical surfaces are measured.

9904-114, Session PS2

High-spatial-frequency diversity for coronagraphic wavefront sensing with COFFEE

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The final performance of current and future instruments dedicated to exoplanet detection and characterization is limited by intensity residuals in the scientific image plane, which originate in uncorrected optical aberrations.

After correction of the atmospheric turbulence in the case of ground-based instruments (such as SPHERE on the VLT, GPI on Gemini South or future instruments on the ELTs), the main contribution to these residuals comes from the quasi-static aberrations introduced upstream of the coronagraph, which create long-lived speckles in the detector plane that can easily be mistaken for planets.

In order to reach very high contrast such as the ones required to image earth-like planets, these aberrations needs to be compensated for. We have proposed a dedicated focal-plane wave-font sensor called COFFEE (for COronagraphic Focal-plane wave-Front Estimation for Exoplanet detection), which consists in an extension of conventional phase diversity to a coronagraphic system: aberrations both upstream and downstream of the coronagraph are estimated using two or three coronagraphic focal-plane images, recorded from the scientific camera itself, without any differential aberration. Such a system has been successfully validated on the SPHERE instrument, where the phase reconstructed with COFFEE has been used to compensate for the aberrations upstream of the coronagraph, leading to a contrast optimization in the whole focal plane area controlled by the adaptive optics loop.

For high contrast space missions, the aimed contrast is several orders of magnitude higher than for the current ground-based dedicated high contrast instruments, and this has at least two consequences. Firstly one must estimate not only phase aberrations but also amplitude aberrations. Secondly, these aberrations must be measured and compensated for all the more frequently as the contrast requirement is more drastic, so the measurement of these aberrations should ideally be made during the scientific observation and not in-between observations.

In this communication, we study the extension of COFFEE to the joint estimation of the phase and the amplitude in the context of space-based coronagraphic instruments. In particular, we show that it is possible to perform estimation of the complex field (phase and amplitude) using a high-spatial-frequency diversity phase such as waffle instead of the defocus (or defocus plus astigmatism) that has been used so far with COFFEE. This way, the impact of the diversity phase is mostly located far away from the star, at the border of the correction region, and the same focal-plane images can be used for scientific exploitation and for wavefront sensing.

Additionally, we optimize the diversity phase in a compromise that minimizes the wavefront estimation while limiting the brightness of the few speckles created by the diversity. Lastly, we assess the wavefront estimation performance of this technique by means of simulations.

9904-116, Session PS2

Demonstration of broadband wavefront control with a shaped pupil Lyot coronagraph for the WFIRST-AFTA Observatory

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A shaped pupil Lyot coronagraph uses an optimized binary pupil-plane mask to suppress light in a localized region of a focal plane 2.8-9 lambda/D from the PSF center, even in the presence of a telescope obscuration and spiders. A focal plane mask sized to that region and a subsequent Lyot stop suppress the starlight further, permitting high contrast imaging at small inner working angles with good tolerances to low-order aberrations. Demonstrations of the performance of this coronagraph have been ongoing as part of the technology development program for WFIRST-AFTA, and we present the results of the WFIRST-AFTA coronagraph milestone 5: demonstration of <9e-9 contrast in a 10% band centered at 550nm with the shaped pupil Lyot coronagraph.

9904-117, Session PS2

High-contrast imaging for complex aperture telescopes (HiCAT): hybrid-shaped pupil: apodized pupil Lyot coronagraph designs for arbitrary apertures

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We present two coronagraph designs adopted for HiCAT. The testbed goals are to study high-contrast imaging strategies for future large segmented telescopes, using starlight suppression with coronagraphy and wavefront control. For the HiCAT coronagraph we developed a hybrid concept by combining an Apodized Pupil Lyot Coronagraph (APLC) with a shaped pupil (SP) apodization, which can be manufactured using black silicon technologies developed for the WFIRST mission. This has the advantage of providing a fully reflective design more favorable for broadband coronagraphic observations. We present the methodology used to optimize these APLC/SP hybrid designs and show an example of a design that could produce a 1e-10 raw contrast dark zone over a 10% bandpass for a large segmented telescope aperture. We apply these results to the case of HiCAT, with a reduced contrast goal for this testbed operating in air, and for two configurations: (i) a design optimized to address all the diffraction features with an on-axis segmented aperture (central obstruction, spiders, segment gaps), (ii) a design optimized for a centrally obstructed circular aperture, for which the effects of the support structures are addressed by the Active Control of Aperture Discontinuities (ACAD) technique, which uses two-Deformable mirrors to remap the beam geometry. We report on the expected performance results of the HiCAT coronagraphs in terms of bandpass, inner working angle, throughput and sensitivity to pointing errors using end-to-end modeling.

9904-118, Session PS2

High-contrast imaging for complex aperture telescopes (HiCAT): first wavefront control results

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Segmented telescopes are a possible approach to enable large-aperture space telescopes for the direct imaging and spectroscopy of habitable worlds. However, the increased complexity of their aperture geometry, due to their central obstruction, support structures and segment gaps, makes high-contrast imaging very challenging. The HiCAT testbed was designed to study and develop solutions for such telescope pupils using wavefront control and starlight suppression. The testbed design has the flexibility to enable studies with increasing complexity for telescope aperture geometries starting with off-axis telescopes, then on-axis telescopes with central obstruction and support structures (e.g. WFIRST), up to on-axis segmented telescopes e.g. including various concepts for a Large UV, Optical, IR telescope (LUVOIR), such as the High Definition Space Telescope (HDST). We completed optical alignment in the summer of 2014 and a first deformable mirror was successfully integrated in the testbed, with a total wavefront error of 13nm RMS over a 18mm diameter circular pupil in open loop. HiCAT will also be provided with a segmented mirror conjugated with a shaped pupil representing the HDST configuration, to directly study wavefront control in the presence of segment gaps, central obstruction and spider. In this communication, we report on the first wavefront control results on HiCAT using a classical Lyot coronagraph, obtained with different methods of wavefront control implemented on the testbed, including Speckle Nulling, Dark Hole and Stroke Minimization, and present a comparison of the resulting contrast level performance.

9904-119, Session PS2

PISCES: The WFIRST coronagraph integral field spectrograph technology demonstrator

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We present the integration and test of the Prototype Imaging Spectrograph for Coronagraphic Exoplanet Studies (PISCES) integral field spectrograph (IFS). The PISCES design meets the science requirements for the Wide-Field InfraRed Survey Telescope (WFIRST) Coronagraph Instrument (CGI) and its performance will be assessed at the High Contrast Imaging Testbed (HCIT) as part of the CGI technology development program. The PISCES instrument was built at NASA Goddard and recently received first light with the Shaped Pupil Coronagraph (SPC) HCIT testbed. The HCIT SPC/PISCES configuration represents the first laboratory demonstration that achieves 10^-9 contrast with an IFS. This is done by incorporating a lenslet array with a pinhole mask in a non-telecentric beam to limit the cross-talk from diffraction between imaging elements. We discuss the alignment and calibration of the spectrograph at Goddard and preliminary results of the HCIT testing at JPL.

9904-121, Session PS2

Recent achievements on ASPIICS: an externally occulted coronagraph for PROBA-3

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This paper presents the current status of ASPIICS, a solar coronagraph that is the primary payload of ESA's formation flying in-orbit demonstration mission PROBA-3.

The "sonic region" of the Sun corona remains extremely difficult to observe with spatial resolution and sensitivity sufficient to understand the fine scale phenomena that govern the quiescent solar corona, as well as phenomena that lead to coronal mass ejections (CMEs), which influence space weather. Improvement on this front requires eclipse-like conditions over long observation times. The space-borne coronagraphs flown so far provided a continuous coverage of the external parts of the corona but their over-occulting system did not permit to analyse the part of the white-light corona where the main coronal mass is concentrated.

The PROBA-3 Coronagraph System, also known as ASPIICS (Association of Spacecraft for Polarimetric and Imaging Investigation of the Corona of the Sun) is designed as a classical externally occulted Lyot coronagraph but it takes advantage of the opportunity to place the external occulter on a companion spacecraft, about 150m apart, to perform high resolution imaging of the inner corona of the Sun as close as ~1.1 solar radii. The images will be tiled and compressed on board in an FPGA before being down-linked to ground for scientific analyses.

ASPIICS is built by a large European consortium including about 20 partners from 7 countries under the auspices of the European Space Agency. This paper is reviewing the recent development status of the ASPIICS instrument as it is approaching CDR.

9904-122, Session PS2

Contrast improvement with imperfect pre-coronagraph and dark-hole

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We have studied a coronagraph system with an unbalanced nulling interferometer (UNI) which considered to be an imperfect (low-contrast) pre-coronagraph. The system consists of an upstream deformable mirror, the pre-coronagraph, a deformable mirror, and a main coronagraph, in sequence. A pre-reduction of the star light to 1/100 at the pre-coronagraph stage enables to enhance the final contrast by 100. It was not operated by the dark-hole control before but a wavefront sensor. We found that the dark-hole control was possible when the pre-coronagraph status could be exchanged between perfect and imperfect nulling. In the style of the nulling interferometer, it could be obtained by phase shift operations. In the case of a focal-plane mask coronagraph it could be obtained by exchanging the masks with a small difference of transmittance pattern. Although we do not make the dark-hole control for the pre-coronagraph, yet, but only for the main coronagraph, it would be promising to implement the dark-hole control for the pre-coronagraph.

We are planning to construct an experimental optics with two vortex mask coronagraphs and two deformable mirrors to validate the techniques. We obtained a contrast of 8E-8 with a vortex mask coronagraph without the pre-coronagraph method where a 12x12 deformable mirror was used. We expect a better contrast if we can use a deformable mirror with more actuators as well as the pre-coronagraph.

9904-123, Session PS2

Low-signal, coronagraphic wavefront estimation with Kalman filtering in the high-contrast imaging testbed

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For direct imaging and spectral characterization of several cold exoplanets in reflected light, the proposed Wide-Field Infrared Survey Telescope-Astrophysics Focused Telescope Assets (WFIRST-AFTA) Coronagraph Instrument (CGI) will carry two types of coronagraphs. The High Contrast Imaging Testbed (HCIT) at the Jet Propulsion Laboratory has been testing both coronagraph types and demonstrated their abilities to achieve high contrast. Focal plane wavefront correction is used to estimate and mitigate aberrations. As the most time-consuming part of correction during a space mission, the acquisition of probed images for electric field estimation needs to be as short as possible. We present results from the HCIT of monochromatic, low-signal wavefront estimation tests using a Shaped Pupil Lyot Coronagraph (SPLC) designed for WFIRST-AFTA. We show that wavefront correction is possible using the minimum theoretical stellar signal in each estimation image. In the low-flux regime, we find that the Kalman filter and iterative extended Kalman filter provide faster correction, better achievable contrast, and more accurate estimates than batch process estimation.

9904-125, Session PS2

Performance results of a starshade at flight Fresnel numbers in the laboratory

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A major science goal of exoplanet exploration is the direct detection and spectral characterization of Earth-like planets. The main challenge with the direct observation of Earth-like extra planets is that these planets are ten billion times fainter than the parent stars and the angular separation between the parent stars and the planets are less than a hundred milliarcseconds.

Many approaches have been suggested over the last couple of decades for imaging these planets. One of the main candidates for creating high-contrast for future Earth-like planets detection is a sharshade. The starshade is a spacecraft flown along the line-of-sight of a space telescope to suppress starlight and enable high-contrast direct imaging of exoplanets. The starshade is typically tens of meters in diameter and the separation from the telescope is of the order of tens of thousands of kilometers. Optical testing of a full-scale starshade on the ground is impossible because of the long separations. Therefore, laboratory verification of starshade designs is necessary to validate the optical models used to design and predict starshade performance.

At Princeton, we have designed and built a testbed that allows verification of scaled starshade at flight-like Fresnel numbers whose suppressed shadow is mathematically identical to that of a space starshade. The goal of this experiment is to demonstrate a pupil plane suppression of better than 1e-9 with a corresponding image plane contrast of better than 1e-11. The starshade testbed uses a 76.4 m optical propagation distance to realize the flight Fresnel number of 14.5. The starshade mask will be placed 38.2 m from the artificial source and the camera is located 38.2 m from the starshade mask. We will use an etched silicon mask as the starshade. The starshade is illuminated by a diverging laser beam to reduce the

aberrations from the collimating optics before the starshade.

We calculate the performance of the laboratory mask under scaled conditions corresponding to a diverging input beam. We generate a two-dimensional mask model with n x n samples and allow the pixels to take on “gray” values (less than 1 but greater than 0) at the petal edges. These gray values are computed via a g x g anti-aliasing subgrid at each edge pixel. A mask model with (n, g) and with radius R will therefore be representative of the resulting feature size given by ?R = 2R/n/g. This feature size of points along the edges represents the accuracy of the polygons used in the CAD model supplied to the Jet Propulsion Laboratory’s Microdevices Lab (MDL) for manufacture. Based on conversations with MDL, we expect that 0.5 ?m feature size is achievable resolution in the mask manufacturing process and is therefore likely the indicator of the best possible performance. We also perform two-dimensional optical propagations with different errors. We find that we can still expect a predicted suppression of better than 1e-9 and the corresponding contrast.

Here, we present first light result of a sample design operating at a flight Fresnel number. We compare the experimental results with simulations that predict the ultimate contrast performance.

9904-126, Session PS2

Results of edge scatter testing for a starshade mission

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In the field of ExoPlanet detection and characterization, the use of a Starshade, an external occulter in front of a telescope at large separations, has been identified as one of the highly promising methods to achieve the goals. Control of scattered sunlight from the edges of the starshade into the telescope was identified as one of the key technology development areas in order to make the starshade feasible (Lawson, JPL D-72279, 2013). Modeling of the scattered light has resulted in very different results (Casement et al., SPIE Vol. 8442, 4H, 2012, Martin et al., SPIE Vol. 8864, 88641A, 2013) so a campaign of experimentation with edge samples was undertaken to attempt to resolve the discrepancies.

Here, we present our results from the measurement of samples of materials which would be suitable for manufacturing the starshade edge and related models. We have focused on coating metallic samples for ease of fabrication: Titanium, Aluminum, and a BerylliumCopper alloy. Using standard machine shop methods, we fabricated samples which had edges with radius of curvature between 10 and 20 microns. We then had these samples coated by two suppliers to evaluate how well these coating types would conform to the edge and provide scatter suppression. The results of scatter measurements of these coated edge samples are presented. In addition, we have subjected these samples to a limited set of environments to evaluate their durability. We will present these results with their impact on the overall starshade mission architecture and error budgets.

9904-127, Session PS2

Ground-based testing and demonstrations of starshades

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The direct detection and characterization of an Earth-like exoplanet is of the highest scientific priority and a leading technology that will enable such discovery is the starshade external occulter. We report on the latest results in ground-based efforts for demonstrating and advancing the technology of starshades.

We report on a recent flight campaign investigating Vertical Takeoff Vertical Landing (VTVL) rockets as a stable platform for a suborbital starshade demonstration. In this campaign supported by the NASA Flight Opportunities Program, we flew a 60 cm starshade on a VTVL rocket and used a suite of sensors to quantify the flight stability of the rocket and its potential as a starshade platform. We also tested a vision-based formation flying sensor that can be used for relative attitude determination and can provide feedback to position the rocket in the line of sight between ground telescope and astronomical target.

Using the McMath-Pierce Solar Telescope at Kitt Peak National Observatory, we are able to keep a stable beam of light from a celestial object behind a starshade to allow for astronomical observations with a starshade. We report on the latest results in which we used a 30 cm starshade to achieve high-contrast images at an inner working angle of 10 arcseconds and at a flight-like Fresnel number.

Finally, we report on the latest results from a NASA Technology Development for Exoplanet Missions (TDEM) study investigating formation flying sensors to enable long range position sensing at the precision needed for a full-scale starshade mission.

9904-128, Session PS2

Diffraction-based analysis of tunnel size for a scaled external occulter testbed

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To test the performance of an external occulter mask (also called a starshade), scaled testbeds have been developed to determine the suppression of the occulter shadow in the pupil plane and measure contrast in the image plane. For occulter experiments the scaling is typically performed by maintaining an equivalent Fresnel number. The original Princeton occulter testbed was oversized with respect to both input beam and shadow propagation to limit any diffraction effects due to laboratory edges; however, to operate at realistic space-mission equivalent Fresnel numbers an extended testbed is currently under construction. With the longer propagation distances involved, diffraction effects due to the edge of the tunnel must now be considered in the experiment design. Here, we present a diffraction-based model of two separate tunnel effects. First, we consider the effect of tunnel-edge induced diffraction ringing upstream from the occulter mask. Second, we consider the diffraction effect due to clipping of the output shadow by the tunnel downstream from the occulter mask. These calculations are performed for the propagation size of the new Princeton occulter experiment, but we also present non-dimensionalized relations that can be used for other propagation distances.

9904-129, Session PS2

Measurements of high-contrast starshade performance in the field

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The external Starshade is a method for the direct detection and spectral characterization of terrestrial planets around other stars, a key goal identified in ASTRO2010. In an effort to validate the starlight-suppression performance of the Starshade, we have measured contrast better than 1X10-9 using 60 cm Starshades at points just beyond the Starshade tips. These measurements were made over a 50% spectral bandpass, using an incoherent light source (a white LED), and in challenging outdoor test environments. Our experimental setup is designed to provide Starshade to telescope separation and telescope aperture size that are scaled as closely as possible to the flight system. The measurements confirm not only the overall starlight-suppression capability of the Starshade concept but also the robustness of the setup to optical disturbances such as atmospheric effects at the test site. The spectral coverage is limited only by the optics and detectors in our test setup, not by the Starshade itself. Here we describe our latest results as well as detailed comparisons of the measured results to model predictions. Plans and status of the next phase of ground testing are also discussed.

9904-130, Session PS2

Engineering considerations applied to starshade repointing

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Using a starshade free-flying in formation with a space telescope provides a method of suppressing starlight to enable spectroscopy and imaging of an exoplanet orbiting its host star. In order to move to observe a different star, the starshade must perform a delta V maneuver to a new orbit location to line up with the telescope's next pointing location. This paper examines some practical engineering aspects of transferring a starshade to a new orbit location that can be used to increase the detail and fidelity of exoplanet yield calculations for a telescope-starshade system. This paper considers a starshade flying in formation with a telescope in Sun-Earth L2 orbit. Orbit dynamics and environmental effects are considered, and a relationship between starshade target slew time and associated propellant expenditure is calculated. The analysis also considers the number of targets that can be observed with respect to propellant consumption.

9904-131, Session PS2

Lenslet array to further suppress star light for direct exoplanet detection

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The direct imaging plays a key role in the detection and characterization of exoplanets orbiting within its host star's habitable zone. Many innovative ideas for starlight suppression and wavefront control have been proposed and developed in the past decade. However, several technological challenges still lie ahead to achieve the required contrast including controlling the observatory jitter performance, tight optical tolerances on starlight masks, the development of wavefront control algorithms, stray light controls, photon counting detectors, and other issues. This paper explores how a lenslet array and pinhole mask may be implemented to further suppress the residual star light. The star shade is used as an example to demonstrate the principal, even though this approach can be implemented for any of the proposed direct exoplanet detection methods. We also discuss how to use a simple relay optics to control the inner working field of view and the level of the suppression is also addressed. Furthermore, if a spectrometer is added after the lenslet array to make it an Integral Field Spectrometer (IFS), the spectral information of the planets can be obtained to determine if the observed planet is inhabited.

9904-133, Session PS2

Orbital differential imaging: a post-processing method enabling the direct detection of an Earth-like planet with a small telescope

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We present the post-processing method that will enable characterization of Earth-like planets with a coronagraphic space telescope dedicated to observing the alpha Centauri system . Orbital differential imaging (ODI) exploits the motion of a planet with respect to the point spread function (PSF). Given repeated high-cadence observations of an exoplanet with a sufficiently short orbital period, orbital motion allows us to discriminate the planet from the PSF. In addition to using powerful PSF subtraction algorithms, time domain analyses can further increase the signal-to-noise ratio. We have developed techniques to model and simulate PSF evolution and speckle dynamics over the years-long timescales under consideration for a dedicated mission. Our simulations suggest that ODI can leverage the large number of images from a small dedicated mission to gain a deeper contrast than would be possible with conventional post-processing techniques or on a mission with many targets. This performance gain potentially enables the direct detection of Earth-like planets in the habitable zone with a space telescope as small as 30-45cm.

9904-134, Session PS2

Synergies of Galaxy Evolution Spectroscopic Explorer (GESE) and Subaru: prime focus spectrograph (PFS)

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The Galaxy Evolution Spectroscopic Explorer (GESE) will obtain UV spectra (0.2-0.4 microns) of redshift, z-1-2 galaxies already observed by Subaru's Hyper Suprime Camera (HSC) and Prime Focus Spectrograph (PFS). The combined spectra of over 50,000 galaxies will cover the spectral range, 0.2-1.3 microns, (e.g. spectra covering 0.1-0.65 microns as emitted by redshift, z=1 galaxies). Knowledge gained from Subaru's HSC and PFS observations (spectroscopic redshifts, colors, coordinates) will enable GESE to identify and acquire its targets efficiently, while GESE will provide a deep g-band image of the field. GESE will obtain unique information on star-formation and stellar feedback and Lyman-? emitting galaxies, while Subaru/PFS will obtain unique information on the growth of stellar mass and stellar feedback, and growth of black holes and AGN feedback. The combined results should lead to a better understanding of the evolution of stars and galaxies over the course of history of the universe.

9904-135, Session PS2

The JWST/NIRSpec exoplanet exposure time calculator

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The James Webb Space Telescope (JWST), with its unprecedented sensitivity, will provide a unique set of tools for the study of transiting exoplanets and their atmospheres. One of these tools is the high-contrast aperture-spectroscopy mode of the near-infrared spectrograph NIRSpec, one of four instruments on JWST.

In this context, we are developing the NIRSpec Exoplanet Exposure Time Calculator (NEETC), which is optimised to deal with observations of transiting exoplanets. It will allow future users to fully investigate NIRSpec's observation modes and capabilities while testing the feasibility of specific observations.

The NEETC differ from a classical ETC in a number of ways. For example, the user can input both stellar and planetary components of the spectrum along with the observation type (transit, eclipse or full phase curve). Simulated spectra will give the user a realistic idea of the quality that can be achieved of a given observation.

The NEETC will also aid the user in the choice of optimal instrument configuration by calculating signal-to-noise ratios for different readout setups. The exposure parameters giving the best duty cycle without saturating the detector will also be an output.

We give examples of how the NEETC can be used to prepare observations, and present examples of outputs and results obtained with the NEETC, higligting the capabilities and limitations of NIRSpec.

9904-136, Session PS2

Exoplanet atmospheres with JWST: degeneracy, systematics, and how to avoid them

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The high sensitivity and broad wavelength coverage of the James Webb Space Telescope will transform the field of exoplanet transit spectroscopy. Transit spectra are inferred from minute, wavelength-dependent variations in the depth of a transit or eclipse as the planet passes in front of or is obscured by its star, and the spectra contain information about the composition, structure and cloudiness of exoplanet atmospheres. Atmospheric retrieval (e.g. Barstow et al. 2013b) is the preferred technique for extracting information from these spectra, but the process can be confused by astrophysical and instrumental systematic noise (Barstow et al. 2013a, Barstow et al. 2015).

We present results of retrieval tests based on synthetic, noisy JWST spectra, for clear and cloudy planets and active and inactive stars. We find that the ability to correct for stellar activity is likely to be a limiting factor for planets orbiting nearby cool stars, as the presence of molecular features in star spots may introduce spurious detections of these gases in a planet's atmosphere.

We discuss the pros and cons of the available JWST instrument combinations for transit spectroscopy, and consider the effect of clouds and aerosols on the spectra. Aerosol high in a planet's atmosphere obscures molecular absorption features in transmission, reducing the information content of spectra in wavelength regions where the cloud is optically thick. We discuss the usefulness of particular wavelength regions for identifying the presence of cloud, and suggest strategies for solving the highly-degenerate retrieval problem for these objects.

Barstow + 2013b MNRAS 434 2616

Barstow + 2013a MNRAS 430 1188

Barstow + 2015 MNRAS 448 2546

9904-137, Session PS2

Archival legacy investigation of circumstellar environments: overview of the debris disk detections

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Over the past three years, we have conducted a comprehensive and consistent re-processing of the HST-NICMOS coronagraphic archive using advanced PSF subtraction methods, entitled the Archival Legacy Investigations of Circumstellar Environments program (ALICE). This virtual campaign of about 400 targets has produced numerous detections of previously unidentified point sources and circumstellar structures. In this publication, we present a summary of our debris disk detections. Debris disks are second-generation dust belts orbiting main sequence stars and are the remnants of the star's planet formation period. In this program, we obtained improved images of 7 debris disks already resolved with NICMOS, and we obtained new images of 10 other debris disks that were either never previously detected with NICMOS or never before imaged in scattered light at all. These images enable a newly comprehensive comparative analysis of a large fraction of all debris disks imaged in scattered light, all imaged by the same instrument in the main infrared filters, reduced in a consistent fashion with a single analysis pipeline, and characterized using the same metrics. We will present the methods used for this study, which includes careful attention to obtaining unbiased measurements by calibration of PSF subtraction algorithm throughputs, and the results of this comparative analysis regarding the morphology and dust properties of these debris disks.

9904-138, Session PS2

An end-to-end simulator of exoplanet transit spectroscopy

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Exoplanet transit spectroscopy has in recent years yielded a number of planetary spectra in both primary and secondary transit, giving us the first insights into the atmospheric composition and characteristics of these distant worlds. A number of dedicated space-borne instruments are being planned to fully realise the potential of this pioneering technique. Instrument simulators have become an integral part of the design process for major astronomical projects. We have designed the first generically applicable, open-access, end-to-end simulator for exoplanet transit spectroscopy ('ExoSim'), which can be modified easily for a number of different telescope designs, and used to simulate observations for these projects.

ExoSim is written in Python and C and utilizes a number of standard Python packages. It has been optimized for speed, efficiency and modularity. A single input XML file is used, that can be modified for different instruments, telescopes, detectors, astronomical objects, and observational modes. ExoSim uses a number of modules and classes to model the various components of the observation in an end-to-end time-domain simulation. These elements include the astrophysical scene, telescope, instrument channels (including all transmissions and emissions), detector, and the observational timeline. ExoSim can draw information directly from the online Open Exoplanet Catalogue and selects stellar Phoenix spectra automatically, allowing it to perform large planet 'surveys' to obtain bulk performance metrics for the instruments concerned. Foregrounds such as zodiacal light (or for ground-based simulations, Earth atmospheric emission and transmission) can be added. Intra- and inter-pixel variations are included, and non-standard point-spread functions can be used as well. The planet input spectrum is used to generate light curves at different wavelengths, which then modulate the stellar spectrum in time. Correlated and uncorrelated noise sources are simulated and include pointing jitter, photon shot and wave noise, read noise and intrinsic detector noise (which includes pixel-to-pixel and time correlations).

Non-destructive reads can be simulated to allow for 'up-the-ramp' or correlated double sampling methods, and a realistic detector 'duty cycle' is used. The output of ExoSim are FITS files containing 'exposures' akin to image files from a real observation, which can then undergo data reduction to extract signal and noise and reconstruct the planetary spectrum.

ExoSim is currently the end-to-end simulator for the Ariel mission, and is being utilized to explore and optimize the instrument design It is also being used to help formulate optimal observational strategies to achieve science goals. We have also developed a version that simulates the Hubble Wide Field Camera 3 infra-red instrument in scanning mode, to investigate the noise characteristics of this instrument which has been used for several exoplanet studies. We are in the process of adding a stellar variability module as a 'plug in' to ExoSim to investigate the effects of stellar astrophysical noise on observations and to study how to decorrelate the effect using multi-wavelength component separation analyses.

ExoSim will also be open access software made available to the astronomical community.

9904-305, Session PS2

Results of ground-based starshade tests

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Starshades are the most promising technology for studying exoplanets. Over the past decade, we have demonstrated the ability of starshades to suppress light from broad-spectrum natural and artificial light sources in test configurations spanning a wide range of Fresnel numbers. The range of test environments includes vacuum chambers, enclosed laboratory environments, and open-air tests. We present a summary of the tests and their results.

9904-139, Session PS3

Far IR surveyor: what lessons can be learned from the JWST experience?

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The Far IR Surveyor (FIS) now under study will be a large cryogenic observatory. The James Webb Space Telescope (JWST) is also a large, cryogenic observatory. Despite the differences in size and temperature, there are definitely lessons spanning the entire life cycle that have been learned on JWST that are applicable to the FAR-IR Surveyor. This paper will introduce a number of these lessons and the rationale for their use by the FIS team. These lessons range from architectural choices to verification.

9904-141, Session PS3

SAFARI optical system architecture and design concept

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SAFARI (SpicA FAR-infrared Instrument) is one of the instruments planned for the SPICA mission. The SPICA mission is the next great leap forward in space-based far-infrared astronomy and will study the evolution of galaxies, stars and planetary systems. SPICA will utilize a deeply cooled 2.5m-class telescope, provided by European industry, to realize zodiacal background limited performance, and high spatial resolution. The instrument SAFARI is a cryogenic grating-based point source spectrometer working in the wavelength domain 34 to 210 ?m, providing spectral resolving power from 300 to at least 3000.

The instrument shall provide low and high resolution spectroscopy in three spectral bands. Low Resolution mode is the native instrument mode, while the high Resolution mode is achieved by means of a Martin-Pupplet interferometer.

The optical system is all-reflective and consists of three main modules; an input optics module, followed by the Band & Mode Distributing Optics and the grating Modules. The instrument utilizes Nyquist sampled filled linear arrays of very sensitive TES detectors.

The work presented in this paper describes the optical design architecture and design concept compatible with the current instrument performance and volume design drivers.

9904-142, Session PS3

Sensitivity estimates for the SPICA mid-infrared instrument (SMI)

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We present the latest results of the sensitivity estimate for SPICA Mid-Infrared Instrument (SMI). SMI has three spectroscopic channels; low resolution spectrometer (LRS), medium resolution spectrometer (MRS) and high resolution spectrometer (HRS). LRS is a multi-slits prism spectrometer covering the wavelength range from 17 micron to 37 micron with a spectral resolution of R=50—120. The spectra along the four long slits, each of which has a size of 3".7 width by 10' length, are obtained on the Si:Sb detector array. MRS is a crossed Echelle grating spectrometer covering the wavelength range from 18 micron to 36 micron with R~1000. The spectra over six different orders from m=6th to 11th along a long slit, which has a size of 3".7 width by 120" length, are obtained on the Si:Sb detector array. HRS is a crossed Echelle immersion grating spectrometer covering the wavelength range from 12 micron to 18.7 micron with R~27,000. The spectra over 34 different orders from 85th to 118th, which successively covers the wavelengths from 12.14 micron to 17.03 micron, and those over 8 different orders from 77th to 84th, which partly covers the wavelengths from 17.03 micron to 18.75 micron, are obtained on the Si:As detector array. Taking account of the results of optical design of each spectrometer and the latest information of the expected performance of detector arrays, the continuum sensitivity for a point source, the continuum sensitivity for an extended source, the line sensitivity for a point source, the line sensitivity for an extended source, and the saturation limit are calculated for LRS, MRS and HRS; e.g., the 1 hour 5-sigma continuum sensitivity for a point source achieved by LRS is ~20 uJy at 20 micron and ~55 uJy at 30 micron, the 1 hour 5-sigma line sensitivity for a point source achieved by MRS is ~3?10^{-20} W/m^{2} at 20 micron and ~5?10^{-20} W/m^{2} at 30 micron, and the 1 hour 5-sigma line sensitivity for a point source achieved by HRS is ~1.5?10^{-20} W/m2^{2} at 15 micron. All the results of our calculations are provided in this presentation.

9904-143, Session PS3

Mechanical cooler system for the next-generation infrared space telescope SPICA

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The Space Infrared Telescope for Cosmology and Astrophysics (SPICA) is a pre-project of JAXA in collaboration with ESA to be launched in the 2020s. The SPICA mission is to be launched into a halo orbit around the second Lagrangian point in the Sun-Earth system, which allows us to use effective radiant cooling in combination with a mechanical cooling system in order to cool a 2.5m-class large IR telescope below 8K. Recently, a new system design in particular thermal structure of the payload module has been studied by considering the technical feasibility of a cryogenic cooled telescope within current constraints of the mission in the CDF (Concurrent Design Facility) study of ESA/ESTEC. Then, the thermal design of the mechanical cooler system, for which Japanese side is responsible, have been examined based on the CDF study and the feasible solution giving a proper margin has been obtained. As a baseline, 4K / 1K-class Joule-Thomson coolers are used to cool the telescope and thermal interface for Focal Plane Instruments (FPIs). Additionally, two sets of double stirling coolers (2STs) are used to cool the Telescope shield. In this design, nominal operation of FPIs can be keeped when one mechanical cooler is in failure.

9904-144, Session PS3

Final photometric calibration of warm IRAC data

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The Spitzer Space Telescope has been conducting a wide range of science investigations including measurement of atmospheric properties of exoplanets and masses of the most distant galaxies during the post-cryogenic operations phase which started in 2009. These investigations using the Infrared Array Camera (IRAC) at 3.6 and 4.5 microns will likely continue through 2018 when the James Webb Space Telescope will succeed Spitzer. In preparation for the eventual end of the mission and exploiting the excellent stability of the instrument and spacecraft, we have finalized the calibrations for the IRAC instrument in advance of the mission end to minimize the cost of the closeout process. The calibrations for the warm mission phase have been substantially revised with the absolute photometric calibration performed with the same methodology as the final cryogenic calibration. We present the revised form of the intra-pixel gain variation and array-location dependent photometric corrections. The absolute photometric calibration is compared with independent ground truth using stellar templates from StScI. The stability of the calibration of IRAC over the duration of the entire mission is examined on both short (days) and long (years) time scales. We discuss the limiting factors to absolute calibration and identify future directions that can be explored in the calibration of JWST, Euclid and WFIRST.

9904-145, Session PS3

Hysteresis in dark patterns in the IRAC InSb arrays in the Spitzer Warm mission

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Images taken with the Infrared Array Camera (IRAC) on the Spitzer Space Telescope have underlying patterns that depend on how the InSb arrays were clocked in the minutes to hours preceding the images. We investigated this dependence by comparing 120000 images of a dark field of the sky at 3.6 and 4.5 microns that were taken in weekly and other calibrations during the first 5 years of the Spitzer Warm Mission. We made a dark image from each raw calibration image by removing the background and masking stars and stray light. IRAC data are taken with Fowler sampling, so the relaxation of the ROIC unit cells and output amplifiers between pedestal and signal samples generates jail bars and a pattern in the dark images that is related to pixel capacitance. For each of the 19 combinations of integration time and clocking speed (fast, sub-array; slow, full-array) in each array, we made a mean weekly dark image and a median image over the weekly darks, then we studied how individual dark images differed from the means. The principal short-term effect on an image is due to the amount of time an array idles between the image and the previous image. There are strong effects that depend on the integration time of the previous frame. The effects of idle times and integration times of preceding images decrease with time. Fast clocking

for a long time adds a different pattern to the darks for minutes to hours. These effects are strong in the 3.6 micron array, and weak at 4.5 microns. In addition to the short-term variations, there was a slow change of the dark pattern at 3.6 microns over the span of 5 years. Latent images appear in nearly every image. In making basic calibrated data (BCDs), the average sky dark from a weekly calibration is subtracted and jail bars are removed. This is a good correction for much of the IRAC data, but it leaves significant residual patterns in BCDs where data were taken either in staring mode or in dithers with more than one frame per pointing. We are developing a multi-parameter dark image model that we expect will provide better dark corrections. We have a model based on one parameter, the idle time preceding a frame, for all kinds of integrations. It was tested on long integrations at 3.6 microns on dithered observations made with more than one frame per pointing. Mosaics made with our corrections had better appearance and lower noise than those made with uncorrected BCDs.

9904-146, Session PS4

Use of living technical budgets to manage risk on the James Webb Space Telescope optical element

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The optical telescope element of the James Webb Space Telescope (JWST) is a three mirror anastigmat design. The Primary Mirror (PM) and Secondary Mirror (SM) are deployable relative to the rest of the optics. The PM consists of 18 segment assemblies which are aligned on-orbit using hexapod actuators. The aligned segments function as a single monolithic optic. The SM also has hexapod actuators for alignment. The complexity of the construction, size, deployments, and active alignments introduces risk that a combination of manufacturing errors and integration misalignments of individual components could result in a system with an unexpected optical train. The result could compromise performance, even with the active control. In order to monitor risk exposure throughout the life of the project, a series of interrelated technical budgets have been created and are continually updated with as-built data to provide confidence in the state of the system as well as the path to completion. Additionally, independent cross-checks of each of the key optical performance characteristics are taken to ensure that no single measurement error could result in a mischaracterized optical system. Measurements taken to-date are presented, indicating the health of the system and setting expected bounds on future measurements planned for later in the program lifecycle.

9904-147, Session PS4

Alignment of the James Webb Space Telescope optical telescope element

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The optical telescope element (OTE) of the James Webb Space Telescope has now been integrated and aligned. The OTE comprises the flight mirrors and the structure that supports them – there are 18 primary mirror segments, the secondary mirror, and the tertiary and fine steering mirrors (both housed in the aft optics subsystem). The primary mirror segments and the secondary mirror have actuators to actively control their positions during operations. This allows the requirements for aligning the OTE subsystems to be in the range of microns rather than nanometers. During OTE integration, the alignment of the major subsystems of the OTE structure and optics are controlled to ensure that, when the telescope is on orbit, the active mirrors are within the adjustment range of the actuators. This paper describes the complex and intricate alignment process and talks about lessons learned in making the alignment process go smoothly. The implications of these lessons for future space observatories are also considered.

9904-150, Session PS4

Characterization of the JWST center of curvature optical assembly (CoCOA) during cryogenic testing of the JWST Pathfinder telescope

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The JWST Optical Telescope Element (OTE) consists of a 6.6 m clear aperture, 18 segment primary mirror, all-reflective, three-mirror anastigmat operating at cryogenic temperatures. To verify performance of the primary mirror, a full aperture center of curvature optical null test is performed under cryogenic conditions in Chamber A at NASA Johnson Space Center. This alignment utilizes a series of optical systems to successfully align the primary mirror. A photogrammetry system and absolute distance meter globally align the mirror and set the RoC. The interferometer within the CoCOA provides feedback to fine align and measure the mirror surface. A software package takes the collected interferometric data and processes it to produce mirror pose corrections to coarse and then fine align the mirror segments. To prepare for the flight test, three cryogenic tests on the JWST Pathfinder are being performed in 2015. As the first opportunity to exercise the system as a whole, a series of tests to characterize the systems capabilities were performed. This paper will discuss the results of the characterizations of the alignment systems, interferometer and the operational aspects of the software to properly globally align and fine phase the primary mirror.

Testing that will be discussed in this paper.

• Ability to globally align the PM to the aft optics subsystem via photogrammetry. Fore optics to aft optics alignment.

• Secondary mirror alignment via photogrammetry.

• Sensitivity testing for coarse and fine alignment of the primary mirror to the null lens/interferometer.

• Reduction of segment level astigmatism vs. global alignment of the CoCOA. Photogrammetry and interferometer measurements will be compared.

• Characterization of the RoC measurement system.

9904-151, Session PS4

MIRI/JWST detector characterization

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We report on tests of the Mid-Infrared Instrument (MIRI) focal plane electronics and detectors conducted at Jet Propulsion Laboratory. Goals of these tests are to: characterize readout mode performance; establish subarray operations; characterize performance changes when switching between subarrays and/or readout modes; fine-tune detector settings to mitigate residual artifacts; optimize anneal effectiveness; and characterize persistence. Testing is part of a continuing effort to support MIRI pipeline development through better understanding of detector behavior. An extensive analysis to determine the readout mode performance was completed. We report specifically on the comparison between fast and slow readout modes and subarray recovery tests.

9904-152, Session PS4

Calibration results using highly aberrated images for aligning the JWST instruments to the telescope

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The James Webb Space Telescope (JWST) project is an international collaboration led by NASA's Goddard Space Flight Center (GSFC) in Greenbelt, MD. JWST is NASA's flagship observatory that will operate nearly a million miles away from Earth at the L2 Lagrange point. JWST's optical design is a three-mirror anastigmat with four main optical components; 1) the eighteen Primary Mirror Segment Assemblies (PMSA), 2) a single Secondary Mirror Assembly (SMA), 3) an Aft-Optics Subsystem (AOS) consisting of a Tertiary Mirror and Fine Steering Mirror, and 4) an Integrated Science Instrument Module consisting of the various instruments for JWST. JWST's optical system has been designed to accommodate a significant amount of alignment capability and risk with the PMSAs and SMA having rigid body motion available on-orbit just for alignment purposes. However, the Aft-Optics Subsystem and Integrated Science Instrument Module (ISIM) are essentially fixed optical subsystems within JWST, and therefore the cryogenic alignment of the Aft-Optics Subsystem (AOS) to the Integrated Science Instrument Module (ISIM) is critical to the optical performance and mission success of JWST.

In support of this cryogenic alignment of the AOS to ISIM, an array of fiber optic sources, known as the AOS Source Plate Assembly (ASPA), are placed near the intermediate image location of JWST (between the secondary and tertiary mirrors) during thermal vacuum ground-test operations. The AOS produces images of the ASPA fiber optic sources at the JWST focal plane location, where they are captured by the various science instruments. In this manner, the AOS provides an optical yardstick by which the instruments within ISIM can evaluate their relative positions to and the alignment of the AOS to ISIM can be quantified. However, since the ASPA is located at the intermediate image location of the JWST three-mirror anastigmat design, the images of these fiber optic sources produced by the AOS are highly aberrated with approximately 2-3μm RMS wavefront error consisting mostly of 3rd-order astigmatism and coma. This is because the elliptical tertiary mirror of the AOS is used off of its ideal foci locations without the compensating wavefront effects of the JWST primary and secondary mirrors. Therefore, the PSFs created are highly asymmetric with relatively complex structure and the centroid and encircled energy analyses traditionally used to locate images are not sufficient for ensuring the AOS to ISIM alignment.

A novel approach combining phase retrieval and spatial metrology was developed to both locate the images with respect to the AOS and provide calibration information for eventual AOS to ISIM alignment verification. During final JWST OTE and ISIM (OTIS) testing, only a single thru-focus image will be collected by the instruments. Therefore, tools and processes were developed to perform single-image phase retrieval on these highly aberrated images such that any single image of the ASPA source can provide calibrated knowledge of the instruments' position relative to the AOS. This paper discusses the results of the methodology, hardware, and calibration performed to ensure that the AOS and ISIM are aligned within their respective tolerances at JWST OTIS testing.

9904-153, Session PS4

The mid-infrared instrument for the James Webb Space Telescope: performance and operation of the low-resolution spectrometer

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We describe here the performance and operational concept for the Low Resolution Spectrometer (LRS) of the mid-infrared instrument (MIRI) for the James Webb Space Telescope. The LRS will provide R~100 long-slit and slitless spectroscopy from 5 to 12 micron, and its design is optimised for observations of compact sources, such as exoplanet host stars. We provide here an overview of the design of the LRS, and its performance as measured during extensive test campaigns, examining in particular the delivered image quality, dispersion, and resolving power, as well as spectrophotometric performance. The instrument also includes a slitless spectroscopy mode, which is optimally suited for transit spectroscopy of exoplanet atmospheres. We provide an overview of the calibration and pipeline procedures currently under development ahead of the JWST launch in 2018.

9904-154, Session PS4

In-orbit commissioning plan for the NIRSpec instrument on the James Webb Space Telescope

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The James Webb Space Telescope (JWST) is a large-aperture, infrared-optimized space telescope, to be launched in late 2018. Following launch, JWST will begin a ~6 month long commissioning campaign, during which all observatory elements will be activated, and their functionality verified. In particular, JWST's segmented primary mirror must be aligned and phased, and all science instruments must demonstrate their expected performance. One of these is the Near-Infrared Spectrograph (NIRSpec) which was designed and built by Airbus GmbH in Ottobrunn (Germany) for the European Space Agency (ESA). NIRSpec is a multi-object spectrograph that will be able to observe up to 100 astronomical objects simultaneously. It has a large field of view (≈3'?3') and is highly sensitive over the wavelength range 0.6?5?m. The main purpose of NIRSpec is to enable low, medium-, and high-resolution NIR spectroscopy in support of all JWST science themes.

Some of the NIRSpec commissioning activities are "functional" in nature, e.g. the power-on of electronics boxes, the verification of mechanism movements, or the active control of contamination heaters during the cooldown phase. Other activities require the collection of detector exposures, either without light (mostly for detector characterization) or with illumination from internal lamps or celestial objects. We describe the currently foreseen implementation for both types of activities, and highlight those that are essential for enabling NIRSpec science as soon as possible after the launch of JWST. In addition, this paper (i) summarizes the objectives of the NIRSpec commissioning campaign, (ii) outlines the sequence of activities needed to achieve these objectives, and (iii) demonstrates that the list of activities is sufficient to enable the full range of NIRSpec observing modes with the specified performance.

9904-156, Session PS4

The spectral calibration of JWST/NIRSpec: results from the recent cryo-vacuum campaign (ISIM-CV3)

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The NIRSpec instrument for the James Webb Space Telescope (JWST) can be operated in multi-object (MOS), long-slit, and integral field modes with spectral resolutions from 100 to 2700. Its MOS mode uses about a quarter of a million individually addressable mini-slits for object selection, covering a field of view of ~ 9 square-arcminute.

We have developed a procedure that uses the calibration data acquired for a limited subset of the NIRSpec modes - and in particular only 1.5% of NIRSpec's a quarter of a million slits - to derive a highly realistic model of the instrument's optical geometry. This allows the light paths within the spectrograph to be accurately computed and, as such, provides the basis for the extraction of wavelength calibrated spectra from NIRSpec data, from any of the apertures, for all modes.

This model-based approach greatly improves the efficiency with which the instrument can be operated. In particular, the conventional approach of carrying separate empirical calibrations for each individual NIRSpec slitlet and each disperser is clearly not practical, and with the model-based approach the need to take matching calibration exposures during each observation is no longer required.

In early 2015, NIRSpec was fitted with new and improved detector arrays and an upgraded Micro Shutter Assembly and in this final flight configuration the instrument has recently undergone a long test campaign, in the large thermal vacuum chamber at NASA's Goddard Space Flight Center, together with the other three scientific instruments installed in the Integrated Science Instrument Module (ISIM) of JWST.

In this contribution, we summarize the procedure that we have undertaken to optimize the values of the model parameters using these recently-acquired data and present the results in terms of the expected spatial and spectral calibration accuracy of NIRSpec.

9904-157, Session PS4

Flat-fielding strategy for JWST/NIRSpec multi-object spectrograph

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The James Webb Space Telescope (JWST) will launch in 2018 with the first ever space-borne Multi-Object Spectrograph (MOS), part of the NIRSpec instrument. NIRSpec contains a suite of 7 dispersive elements and 8 filters to cover the wavelength range 0.6–5?m at 3 spectral resolutions. The MOS comprises a quarter of a million shutters which can be individually addressed to select up to 100 target objects within a ~3.2x3.4 arcmin field of view.

In this paper we present the strategy for flat-fielding MOS observations from NIRSpec. The flat-field is used to correct for the combined effects of the full telescope throughput (observatory and instrument) and detector response, and is therefore a function of wavelength, field angle and incident pixel.

For NIRSpec MOS observations, the correspondence between wavelength and pixel depends on which micro-shutters are configured open. Concerns for observatory efficiency and persistence effects dictate that a dedicated flat-field observation per configuration is unsupportable, and there are too many possibilities for all shutters to be covered by a complete set of calibration exposures. Consequently, a well-designed calibration campaign, employing a sub-set of available shutters, must provide a universal flat-field reference cube to be used for all MOS observations.

We describe the two-step strategy envisaged. 1) The observations and processing required to create the flat-field reference cube, which includes an algorithm to remove the intrinsic grid-like shadowing pattern caused by the micro-shutter frame. 2) The on-the-fly generation of a 2D flat-field frame for any specific MOS configuration, including estimates of uncertainty from interpolation. After launch the flat-field cube will encapsulate the full throughput, with absolute calibration via spectro-photometric standard star observations across the field. The flat-field cubes presented here originate from internal calibration lamp exposures in late 2015, which do not include the telescope and instrument fore-optics. Finally, we briefly discuss plans for the implementation of this strategy within the automatic data processing pipeline.

9904-158, Session PS4

The James Webb Space Telescope NIRISS optical simulator

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The Near Infrared Imager and Slitless Spectrograph (NIRISS) Optical Simulator (NOS) is a laboratory simulation of the single-object slitless spectrograph and aperture masking interferometry modes of the NIRISS instrument onboard the James Webb Space Telescope (JWST). A transiting exoplanet will be simulated by periodically eclipsing a small portion (1% - 10ppm) of a super continuum laser source (.7?m-2.9?m) with a methyl chloride filled container. Methyl chloride exhibits multiple absorption features in the infrared domain hence the net effect is analogous to the atmospheric absorption features of an exoplanet transiting in front of its host star. The NOS uses an HAWAII-2RG and an ASIC controller cooled to liquid nitrogen temperatures. A separate photometric beacon provides a flux reference to monitor laser variations. The telescope jitter will be simulated using a high-resolution motorized pinhole placed along the optical path. White light curves and transiting spectroscopy data will be produced from this simulation to refine the analysis methods, characterise the noise due to the jitter, to characterize the noise floor and to develop better observation strategies.

9904-159, Session PS4

In-focus phase retrieval using JWST-NIRISS's non-redundant mask

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The James Webb Space Telescope's Near InfraRed Imager and Slitless Spectrograph (NIRISS) contains a 7-hole non-redundant mask (NRM) in its pupil. NIRISS's Aperture Masking Interferometry (AMI) mode is useful both for science as well as wavefront sensing. In-focus science detector NRM and full pupil images of unresolved stars can be used to measure the wavefront without any dedicated wavefront sensing hardware or moving mirrors. Using routine science operational sequences, these images can be taken prior to any science visit. We demonstrate that consecutive masked and unmasked exposures provide enough information to reconstruct a wavefront with up to ~1-2 radians of error. NRM fringe phases constrain Gerchberg-Saxton phase retrieval to disambiguate the sign of the phase error. We present results using this approach for both simulation and laboratory experiments, in the context of contingency for JWST segment phasing.

We discuss extending our method to ground-based AO systems and future space telescopes.

9904-160, Session PS4

Aperture masking interferometry with JWST NIRISS: performance predictions from ground testing

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The Aperture Masking Interferometry (AMI) mode of the James Webb Space Telescope's Near Infrared Imager and Slitless Spectrograph (JWST NIRISS) has undergone three cryovac tests at Goddard Space Flight Center. The third test utilized the flight detector. We report on performance predictions of in-flight science observations, and advances in data reduction methods applicable to this mode. This informs the types of early science NIRISS AMI can do during commissioning and early science observations. The stability enabled by space-based imaging with the non-redundant mask (NRM) that the AMI mode uses should support improved astrometry compared to similar ground-based NRM imaging. We use image-plane-based data analysis methods to recover interferometric fringe amplitudes and visibilities of cryovac data, and demonstrate refined measures of the position of a point source. This analysis yields the pixel scale(s) and the overall NRM pupil geometry. We also assess the stability of fringe amplitude measurements with the flight detector, as these quantities measure centro-symmetric extended structure around a point source. In order to perform these measurements we refined the analytical model of the NRM PSF to incorporate linear distortions and pupil rotation using the Lacour-Greenbaum NRM-specific data analysis algorithm that is used in the science data reduction pipeline for JWST NIRISS AMI data.

9904-161, Session PS4

Alignment test results of the JWST Pathfinder Telescope mirrors in the cryogenic environment

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After integration of the Optical Telescope Element (OTE) to the Integrated Science Instrument Module (ISIM) to become the OTIS, the James Webb Space Telescope OTIS is tested at NASA's Johnson Space Center (JSC) in the cryogenic vacuum Chamber A for alignment and optical performance.

Is space, the mirrors are aligned using the images from a known star onto the Science Instrument detectors. On earth in the chamber at cryogenic temperatures, the mirrors are aligned using photogrammetry cameras with reflective targets attached to the sides of the mirrors. Then a multi-wavelength interferometer is aligned to the 18-segment primary mirror using cameras at the center of curvature to align reflected light from the segments and using fiducials at the edge of the primary mirror. Once the interferometer is aligned, the 18 primary mirror segments are then adjusted to optimize wavefront error of the aggregate mirror. This process phases the piston and tilt positions of all the mirror segments. Then an optical fiber placed at the Cassegrain focus of the telescope emits light towards the secondary mirror to create a collimated beam emitting from the primary mirror. Portions of the collimated beam are retro-reflected from flat mirrors at the top of the chamber to pass through the telescope to the S detector. The image on the detector is used for fine alignment of the secondary mirror and a check of the primary mirror alignment using many of the same analysis techniques used in the on-orbit alignment.

The entire process was practiced and evaluated in 2015 at cryogenic temperature with the Pathfinder telescope, the Aft Optics Subsystem from the OTIS, and with a Beam Image Analyzer (BIA) placed at the telescope image. The process included the exercise of the operation, the data flow, and the in-situ analysis. The Pathfinder telescope includes 2 primary mirror segments and a secondary mirror. The entire process will be reviewed with images from the cameras and detectors. The resulting alignment results will be discussed with the alignment uncertainties and other related learning. Although the telescope is on the order of 10 meters in size, the mirrors are aligned to a small fraction of a millimeter, and the segments are phased to a fraction of a visible wavelength. The results show excellent preparedness for the alignment of the OTIS in the chamber at cryogenic temperatures.

9904-162, Session PS4

James Webb Space Telescope optical simulation testbed III first experimental results with linear-control alignment

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The James Webb Space Telescope (JWST) Optical Simulation Testbed (JOST) is a tabletop experiment designed to study wavefront sensing and control for a segmented space telescope, including both commissioning and maintenance activities. JOST is complementary to existing testbeds for JWST (e.g. the Ball Aerospace Testbed Telescope TBT) given its compact scale and flexibility, ease of use, and colocation at the JWST Science & Operations Center. The design of JOST reproduces the physics of JWST's three-mirror anastigmat (TMA) using three custom aspheric lenses. It provides similar quality image as JWST (80% Strehl ratio) over a field equivalent to a NIRCam module, but at 633 nm. An Iris AO segmented mirror stands for the segmented primary mirror of JWST. Actuators allow us to control (1) the 18 segments of the segmented mirror in piston, tip, tilt and (2) the second lens, which stands for the secondary mirror, in tip, tilt and x, y, z positions. We present the experimental optical quality of the testbed evaluated using phase retrieval sensing, and study the linearity of the main aberration modes (focus, astigmatism, coma) both as a function of the field point and level of misalignment of the secondary mirror. We present the linear control alignment strategy developed for the testbed, and illustrate its performance by reproducing some of the main phases of the JWST commissioning from an initial misaligned state.

9904-163, Session PS4

A new method of superbias construction for NIRCam

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The subtraction of a superbias image from NIRCam data is an essential step in the calibration process. Only by removing the bias signal is it possible to observe more subtle electronic noise effects in the data (e.g. 1/f noise).

We have developed a new technique to construct superbias images from NIRCam data. We measure and subtract the 1/f noise from a series of dark current observations, leaving behind only bias signal.

Averaging multiple integrations together, we construct a superbias image with significantly lower noise than can be achieved using the traditional line-fitting technique.

We find that with only 15-20 shortwave channel dark current integrations, one can create a superbias image in which the readnoise and residual 1/f noise contributions have been reduced to negligible levels for the purposes of data calibration. Tests show that using this superbias as part of the standard data reduction scheme results in calibrated frames with noise levels approaching the kTc noise floor, implying that other noise sources have been successfully made irrelevant.

9904-164, Session PS4

Wavefront-error performance characterization for the James Webb Space Telescope (JWST) integrated science instrument module (ISIM) science instruments

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The science instruments (SIs) comprising the James Webb Space Telescope (JWST) Integrated Science Instrument Module (ISIM) were tested in three cryogenic-vacuum test campaigns in the NASA Goddard Space Flight Center (GSFC)'s Space Environment Simulator (SES).

In this paper, we describe the results of optical wavefront-error performance characterization of the SIs. The wavefront error is determined using image-based wavefront sensing (also known as phase retrieval), and the primary data used by this process are focus sweeps, a series of images recorded by the instrument under test in its as-used configuration, in which the focal plane is systematically changed from one image to the next. High-precision determination of the wavefront error also requires several sources of secondary data, including 1) spectrum, apodization, and wavefront-error characterization of the optical ground-support equipment (OGSE) illumination module, called the OTE Simulator (OSIM), 2) plate scale measurements made using a Pseudo-Nonredundant Mask (PNRM), and 3) pupil geometry predictions as a function of SI and field point, which are complicated because of a tricontagon-shaped outer perimeter and small holes that appear in the exit pupil due to the way that different light sources are injected into the optical path by the OGSE. One set of wavefront-error tests, for the coronagraphic channel of the Near-Infrared Camera (NIRCam) Longwave instruments, was performed using data from transverse translation diversity sweeps instead of focus sweeps, in which a sub-aperture is translated and/or rotated across the exit pupil of the system.

Several optical-performance requirements that were verified during this ISIM-level testing are levied on the uncertainties of various wavefront-error-related quantities rather than on the wavefront errors themselves. This paper also describes the methodology, based on Monte Carlo simulations of the wavefront-sensing analysis of focus-sweep data, used to establish the uncertainties of the wavefront error maps.

9904-166, Session PS4

Model predictions and observed performance of JWST cryogenic position metrology system

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The James Webb Space Telescope cryogenic testing has begun at the Johnson Spaceflight Center's Chamber A and requires measurement systems that both obtain a very high degree of accuracy and can function in a high vacuum, low temperature environment. Close-range photogrammetry was identified as meeting those criteria.

Testing the capability of a close-range photogrammetric system prior to its existence is a challenging problem. Computer simulation was chosen over building a scaled mock-up, because of the size and complexity of the experiment. Before any of the hardware was in the chamber the entire photogrammetry system as well as all the hardware was simulated to generate synthetic images representative of what the actual camera systems would see. The simulated images were generated using the Digital Image and Remote Sensing Image Generation, DIRSIG, tool. DIRSIG is a physics-based first principles radiometric image generation software that is extensively used in the remote sensing community.

The created model included CAD-based representation of all of the key objects inside the chamber, including the chamber itself, the flash level expected from the camera system as the sole source of illumination, and the experimentally derived properties of the reflective materials to be used for photogrammetry targets. The most challenging material to measure and model was the retroreflective target material.

Models for each phase of chamber testing were created and used to test proposed camera pointing sequences and target configurations. By using this approach, best case solutions and optimum trade-offs were achieved for when the actual system was used inside the chamber.

Extensive validation work was done to ensure that the actual as-built system meet accuracy and repeatability requirements and the results were also compared to the model predictions. The simulated image data when passed through the photogrammetry software predicted the uncertainty in measurement to be within specification and this prediction proved to be borne out by the initial tests accomplished in Chamber A.

9904-167, Session PS4

Updated cryogenic performance test results for the flight model JWST fine guidance sensor

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The Integrated Science Instrument Module (ISIM) for the James Webb Space Telescope (JWST) has successfully completed its final cryogenic performance verification tests. The performance of the newly upgraded Fine Guidance Sensor (FGS) / Near Infrared Imager and Slitless Spectrometer (NIRISS) was evaluated in these tests. We describe some of the key guider performance results which have been obtained and compare them to previous results with an older generation of H2RG infrared detector arrays. The identification mode sensitivity improvement is described along with noise equivalent angle (NEA) performance improvements in tracking and fine guiding modes. Tracking mode allows the Observatory line of sight to settle in advance of the fine guidance mode and also facilitates moving target observing. The NEA of the FGS-Guiders will in part determine the ultimate image quality of the JWST Observatory.

9904-251, Session PS4

Performance of the primary mirror center-of-curvature optical metrology system during cryogenic testing of the JWST Pathfinder Telescope

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The James Webb Space Telescope (JWST) primary mirror (PM) is 6.6 m in diameter and consists of 18 hexagonal segments, each 1.5 m point-to-point. Each segment has a six degree-of-freedom hexapod actuation system and a radius-of-curvature (RoC) actuation system. The full telescope will be tested at its cryogenic operating temperature at Johnson Space Center. This testing will include center-of-curvature measurements of the PM, using the Center-of-Curvature Optical Assembly (COCOA) and the Absolute Distance Meter Assembly (ADMA). The COCOA includes an interferometer, a reflective null, an interferometer-null calibration system, coarse & fine alignment systems, and two displacement measuring interferometer systems. A multiple-wavelength interferometer (MWIF) is used to enable alignment & phasing of the PM segments. By combining measurements at two laser wavelengths, synthetic wavelengths up to 15 mm can be achieved, allowing mirror segments with millimeter-level piston errors to be phased to the nanometer level. The ADMA is used to measure, and set, the spacing between the PM and the focus of the COCOA null (i.e. the PM center-of-curvature) for determination of the RoC. The performance of these metrology systems, along with that of all the other ground support equipment to be used during the flight telescope testing, was assessed during two recent cryogenic tests at JSC. This testing was performed using the JWST Pathfinder telescope, consisting mostly of engineering development & spare hardware. The Pathfinder PM consists of two spare segments. These tests provided the opportunity to assess how well the center-of-curvature optical metrology hardware, along with the software & procedures, performed using real JWST telescope hardware. This paper will describe the test setup, the testing performed, and the resulting metrology system performance. The knowledge gained and the lessons learned during this testing will be of great benefit to the accurate & efficient cryogenic testing of the JWST flight telescope.

9904-168, Session PS5

On the performance of the Gaia auto-collimating flat mirror assembly: could it be even better?

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The Auto-collimating Flat Mirror Assembly (AFMA) simulated the spinning of the Gaia satellite around its vertical axis. As such, it was one of the most important ground support equipment tools to test the payload performance of the Gaia mission. A laser point source, positioned at a CCD-array, is retro reflected onto the CCD-array via a scanning auto-collimating mirror positioned opposite to Gaia's telescope mirror.

The scanning performance around the vertical axis (azimuth), with a 20 mrad range and nrad stability requirement, was most critical.

TNO already delivered two compliant AFMA's a couple of years ago, but meeting the required nrad stability has been a big challenge in the project. In particular, providing accurate predictions of the system dynamics and positioning performance in the design phase of the project, and correlating them to later measurements was not a trivial task. This was partly caused by ground vibrations and the dynamic interaction with the back structure, mostly low-frequent in nature, which were contributing most to the steady-state position error. To suppress these low-frequent contributions, sufficient disturbance suppression at these frequencies is required. This results in requirements for the controller sensitivity at these frequencies and thus the controller bandwidth; the controller sensitivity (below the controller bandwidth) automatically decreases when the controller bandwidth of the system is increased However, achieving the

required bandwidth was challenging, mainly because of some interesting discrepancies between the predicted and measured open loop transfer functions.

Although AFMA eventually performed within spec, using improved ground vibration suppression, an advanced controller, and minor tweaks in the mechanical design, some of the dynamical behaviour could not be fully explained. Therefore, the dynamic behaviour of Gaia AFMA has recently again been analysed and back-engineered.

First, the mechanical design has been analysed; AFMA is a box-in-a-box design, with a rotating (inner) box connected to a fixed (outer) box. A virtual axis of rotation for the scanning motion is positioned at the front surface of a SiC mirror, which is created by an elastic cross-hinge. This cross-hinge is assembled with two stiffened flexure hinges. The mirror is connected to the rotating (inner) box, and the cross-hinge connects this rotating box to the fixed (outer) box. The scanning motion is actuated by two modules connected to the outer box. Design improvements on these scanning modules have been developed.

Furthermore, dynamic analyses have been performed, starting with a comparison of a 1D dynamical model comprising of a mass-spring-damper model, with actual measurements..

Next, a simplified 3D CAD model is implemented in FEM and a modal analysis has been performed. With the information of the modal analysis, and by defining the in- and outputs, a modal state space description is obtained, being able to simulate an FRF to compare with the measurements. Also, an experimental modal analysis (EMA) has been performed and compared to the finite element analysis (FEA). The main dynamical problems are pointed out, and possible design improvements have been derived.

9904-169, Session PS5

How mission requirements affect the observations: case of the PICARD mission

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The scientific objectives of a space mission translate into instrumental developments and satellites operations to observe the astronomical objects of interest. The payload in its space environment is however subject to important thermal variations that affect the observations. This is well observed when images of the Sun are recorded with the constraint of having the solar rotational axis in a constant direction relatively to the camera reference system. Consequences are then clearly observed on the image positions that follow the thermal variations on the satellite orbit. This is particularly the case for the PICARD space mission. This phenomenon is similar to the defocus and motions of the images recorded with ground-based telescopes. We will present in this work some simulations showing this effect in space. We will then compare our results with real data obtained from the PICARD solar mission.

9904-170, Session PS5

Optical designing of LiteBIRD

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The scientific purpose of LiteBIRD (Lite (Light) satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection) is to reveal the era before the big bang. In this inflation era immediately after the beginning of the universe, the universe is believed to have exponentially expanded and to have produced the primordial gravitational wave. LiteBIRD aims to detect the footprint of this wave on the Cosmic Microwave Background (CMB) in a form of special polarization pattern called B mode. For this we will reach the tensor/scalar ratio of $r<0.001$, by carrying out three-year measurements of linear polarization of the CMB in the whole sky.

The CMB has its emission peak at millimeter wavelength. In order to separate it from the Galactic emission including the synchrotron and the dust emission, our measurements cover the wide frequency range of 35GHz to 450GHz.

The LiteBIRD optics consists of crossed Dragone type, which provides a compact configuration with a wide field of view. Both of the primary and secondary reflectors have anamorphic non-spherical surfaces. A continuously rotating half-wave plate modulator is placed at the aperture position, facing directly to the sky, and separates the sky linear polarization from the artificially produced one. The whole optical system is cooled down to around 4K to minimize the thermal emission. We are now developing the design, including the selection of mirror material.

We use two kinds of approaches: searching proper design candidates with the ray tracing, and obtaining the strict design solution around such candidates by using the physical optics (GRASP). We have carried out tradeoff studies including the optical system size and the stray light avoidance. Furthermore, in order to confirm the accuracy of the GRASP calculation, particularly in terms of detailed baffle/hood designs, we have produced a 1/3 scale model aluminum mirror and are pursuing radio property measurements at 200GHz. This corresponds to 60GHz in a full model.

The candidate materials for mirrors are CFRP, C/SiC, SiC, and aluminum. We are measuring mechanical and thermal properties of these candidate materials. If we select honeycomb structure of CFRP, which has advantages in weight and in coefficient of thermal expansion, it is concerned that it might have dimpling caused by this structure. The dimpling might give additional errors on polarization measurements disturbing the beam shapes. We have developed the method to treat this effect quantitatively in designing, which enables us to select the mirror material in an appropriate way.

9904-171, Session PS5

Polarization modulator for LiteBIRD

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LiteBIRD is a next generation cosmic microwave background polarization satellite to measure the primordial B-mode, fingerprints of the cosmic inflation. The science goal of LiteBIRD is to measure the tensor-to-scalar ratio with the sensitivity of sigma(r) < 0.001. LiteBIRD observes the fully sky by spinning the satellite at the seond Lagrange point for three years. The baseline design of a mission instrument covers the observational frequency of 40-400 GHz. A telescope consists of a cryogenically cooled optical system and about 2,000 superconducting detector arrays at 100 mK cooled by a sub-kelvin cooler. LiteBIRD is currently under the transition toward Phase-A. The targeted launch year is in early 2020s.

The sensitivity of LiteBIRD requires the stringent control of stability in the detector chain and the systematic errors. One possibility to suppress those effects is to introduce a polarization modulator in the mission system in addition to the optimal scan strategy. The required functionalities are to up-convert the signal and also to treat each linearly polarized sensitive detector independently. A continuously rotating cryogenically cooled achromatic half-wave plate can supply the required functionality. We introduce the pros and cons of introducing the polarization modulator, and discuss the feasibility of its implementation to a satellite platform. We also discuss the current status of the two major developments, a cryogenically cooled rotation system and an achromatic half-wave plate.

9904-172, Session PS5

The cosmic infrared background experiment-2 (CIBER-2) for studying the near-infrared extragalactic background light

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We present the current status of the Cosmic Infrared Background ExpeRiment-2 (CIBER-2) project, whose goal is to make a rocket-borne measurement of the near-infrared Extragalactic Background Light (EBL), under collaborate with U.S.A., South Korea, and Taiwan.

The Extragalactic Background Light is the integrated light of all extragalactic sources of emission back to the early Universe. At near-infrared wavelengths, measurement of the EBL is a promising way to detect the diffuse light from the first collapsed structures at redshift z~10, which are impossible to detect as individual sources. However, recently, the intra-halo light (IHL) model is advocated as the main contribution to the EBL, and our new result of the EBL fluctuation from CIBER experiment is also supporting this model. In this model, EBL is contributed by accumulated light from stars in the dark halo regions of low-redshift (z<2) galaxies, those were tidally stripped by the interaction of satellite dwarf galaxies. Thus, in order to understand the origin of the EBL, both the spatial fluctuation observations with multiple wavelength bands and the absolute spectroscopic observations for the EBL are highly required.

After the successful initial CIBER experiment, we are now developing a new instrument CIBER-2, which is comprised of a 28.5-cm aluminum telescope and three broad-band, wide-field imaging cameras. The three wide-field (2.3x2.3 degrees) imaging cameras use the 2Kx2K HgCdTe HAWAII-2RG arrays, and cover the near-infrared wavelength range of 0.5--0.9 um, 0.9--1.4 um and 1.4--2.0 um, respectively. Combining a large area telescope with the high sensitivity detectors, CIBER-2 will be able to measure the spatial fluctuations in the EBL at much fainter levels than those detected in previous CIBER experiment. Additionally, we will use a linear variable filter installed just above the detectors so that a measurement of the absolute spectrum of the EBL is also possible.

In this paper, the scientific motivation and the expected performance for CIBER-2 will be presented. The detailed designs of the telescope and imaging cameras will also be discussed, including the designs of the mechanical, cryogenic, and electrical systems.

9904-173, Session PS5

Prime focus architectures for large space telescopes

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Conceptual architectures are now being developed to identify future mission & technology directions for post JWST large space telescope systems. With few exceptions, current space telescope architectures are founded on systems optimized for ground-based astronomy. Both HST and JWST are classical Cassegrain space telescopes derived from the ground-based requirement to co-locate the massive primary mirror and the instruments at the same end of the metrology structure. This requirement derives from the dual need to 1. Minimize observatory dome size & cost in the presence of the Earth's 1-g gravitational field and 2. Let the astronomer view through a convenient eyepiece while near the observing floor. Space telescopes, however function in the zero gravity of space, without an observatory dome and the 1-g constraint is relieved to the advantage of astronomers. Prime focus telescope systems in space potentially have higher transmittance, better pointing, improved thermal and structural control, less internal polarization and broader wavelength coverage than Cassegrain telescopes. This architecture is particularly suited to the evolvable space telescope (EST). This paper discusses several prime focus space telescope architectures within the framework of the astronomical science measurement objectives as presented and prioritized by NASA science advisory committees.

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9904-174, Session PS5

Reaching sub-milimag photometric precision on Beta Pic with a nanosat: the PicSat mission payload

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Beta Pictoris (HD 39060) is an A6V star of magnitude 3.86 (V band) which, due to its proximity (~20 pc from Earth), youth (~12 Myr), and the presence of a circumstellar disk (discovered in 1984), has always been a most promising target for the study of circumstellar environment and planetary systems.

In 2003, beta Pictoris b, a young giant exoplanet, was directly imaged around this star. Its orbit was latter characterized using multiple astrometric position measurements acquired from 2009 to 2013, and it is now strongly suspected that this is a transiting exoplanet, with a next transit event expected for mid 2017 or late 2018. This represents a unique window of opportunity to finely characterize a young giant exoplanet and its close environment (Hill sphere).

To take advantage of this possibility, a nanosatellite is currently being developed to observe the transit. The PicSat mission is based on a 3U Cubesat architecture, with a small but ambitious ~1 kg opto-mechanical payload specifically designed for high precision photometry. The satellite is planned to be launched in early 2017, on a 600 km Sun synchronous orbit. The main objective of the mission is the constant monitoring of the brightness of beta Pic at an unprecedented combination of reliability and precision (200 ppm per hour, with interruptions of at most 30 minutes) to finely characterize the transiting exoplanet and detect exocomets in the beta Pictoris system.

To achieve this difficult objective, the payload is designed with a 3.5 cm effective aperture telescope which injects the light in a single-mode optical fiber linked to an avalanche photodiode. A two-axis piezoelectric actuation system, driven by a tailor-made feedback loop control algorithm, is used to lock the fiber on the center of the star in the focal plane. These actuators complement the attitude determination and control system of the satellite to maintain the sub-arcsecond pointing accuracy required to reach the excellent level of photometric precision. Overall, the mission raises multiple very difficult challenges: high temperature stability of the avalanche detector (achieved with a thermoelectric cooler module), high pointing accuracy and stability, and short timeframe for the development.

We will present the science objectives of the PicSat mission, discuss the design of its high precision photometric payload, and detail the tracking algorithm used to lock the fiber on the star in the focal plane.

9904-175, Session PS5

Twinkle: a low earth orbit visible and infrared exoplanet spectroscopy observatory

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Twinkle is a space mission dedicated to the spectroscopic observation of the atmospheres of extrasolar planets. With the recent discovery of almost 2000 exoplanets, there is a need to move from the single detection of molecular species in given exoplanets to statistical observation of molecular species in such bodies to understand the likeliness of given planetary systems.

Twinkle is a small dedicated satellite with a payload designed to optimize the spectroscopy observations while adapting to the design of an existing Low Earth Orbit commercial satellite platform. The SSTL-300 bus to be launched into a low-Earth sun-synchronous polar orbit by 2019 would carry a half-metre class telescope with two instruments (visible and near-IR spectrographs -between 0.5 and 4.5μm - with resolving power R~300 at the lower end of the wavelength scale) using mostly flight proven spacecraft systems designed by Surrey Satellite Technology Ltd and a combination of high TRL instrumentation and a few lower TRL elements built by a consortium of UK institutes. During its 5 years of operation, Twinkle will observe in excess of a hundred known exoplanets with the potential of discovering the presence of a large number of molecular species.

9904-176, Session PS5

The infrared spectrometer for Twinkle

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Twinkle is a small satellite mission to observe the atmospheres of exoplanets in the visible to near infrared. This paper describes the design of the infrared (1.3 to 4.5 micron) spectrometer which works at the diffraction limit of the 450mm diameter telescope and at a resolving power of 300 (1.3-2.4 microns) and, in order to achieve the required SNR, R=30 for 2.4-4.5 microns. The planetary spectrum is obtained by taking differences between the spectra of star + planet at different phases of the planet's orbit so there is an emphasis of spectral and radiometric stability. The design incorporates a number of features to enhance this stability

- compact all aluminium structure and mirror substrates to reduce alignment offsets when cooled to the operating temperature of ~100K

- pupil imaging in the across dispersion direction to minimise changes due to sub-pixel variations in sensitivity and reduce the number of illuminated pixels for background measurements

9904-177, Session PS5

ACCESS: integration, pre-flight performance, and calibration

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Using SNeIa to distinguish dark energy models from one another levies a requirement for 1% precision in the cross-color calibration of the SNe Ia flux across a bandpass extending from 0.35 ? 1.7 ?m. The systematic errors in the flux calibration network spanning the visible through the NIR currently exceed 1%. ACCESS, Absolute Color Calibration Experiment for Standard

Stars, is a series of rocket-borne sub-orbital missions and ground-based experiments that will leverage the significant technological advances in detectors, instruments, and the precision of the fundamental laboratory standards used to calibrate these instruments to enable improvements in the precision of the astrophysical flux scale through the transfer of absolute laboratory detector standards from the National Institute of Standards and Technology (NIST) to a network of stellar standards with a calibration accuracy of 1% and a spectral resolving power of 500 across the 0.35 to 1.7 micron bandpass. The ACCESS Cassegrain telescope feeds a compact (Rowland circle design) spectrograph with a cross dispersing Fery prism.

The detector, a HST/WFC3 heritage 1024x1024 HgCdTe array, is sensitive across the full 0.35 to 1.7 micron bandpass. Vibration and thermal vacuum testing of the detector have been successful. Ground-based detector characterization is on-going. The thermal vacuum system is being assembled and tested. The ACCESS telescope and spectrograph are currently in stages of assembly, test, and integration. Integration and alignment of the spectrograph optics will be described. Calibration strategy and status, ground-based integration, vibration testing and instrument performance results will be presented. Launch is expected within the year. NASA sounding rocket grant NNX14AH48G supports this work.

9904-178, Session PS5

CALISTO: a single-aperture far-IR surveyor concept

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We present a study of the scientific requirements and implementation options for a wide-field cryogenic telescope architecture for the Far-Infrared Surveyor. The starting point is the actively-cooled 4x6-meter CALISTO concept, but we are including advanced imaging and spectroscopic instrumentation covering 30-600 microns, operating at the photon background limit, with a total detector count of a few hundred thousand, a 100-fold increase at these wavelengths.

A sensitive far-IR space capability is a long-term astrophysics imperative for NASA. Integrated over cosmic time, most of the energy released by star formation and black hole growth in galaxies emerges in the far-IR, yet this band is inaccessible from the ground. The rest-frame mid- to far-IR both measures the total bolometric energy release, and provides direct access to the inner workings of galaxies and Galactic star-forming regions. Particularly compelling are the suite of powerful spectroscopic diagnostics that measure redshifts as well as the properties of gas at the interaction between energy sources and their surrounding interstellar material. In aggregate, sensitive far-IR measurements will: measure the onset of heavy elements and organic molecules, chart the total history of star formation (including that in galaxies below the individual detection threshold), probe the cycling of matter and energy in the Milky Way, and conduct a census of gas mass and conditions in protoplanetary disks throughout their evolutionary sequence.

The scientific investigations require excellent spectroscopic and surface-brightness sensitivity only possible with an actively-cooled telescope. A large 4-K system is new, but all individual technologies have been demonstrated. Scaling from experience with Planck indicates that the combination of V-groove radiators and an active heat lift of ~2 W at T~20 K and 150 mW at 4 K should overcome the telescope parasitics as well as the heat rejected by the sub-K instrument coolers. These heat lifts can be provided with 4He closed-cycle coolers, with a total observatory power below 1500 W. We study the impact of on-axis vs off-axis telescope design, and consider the possibility of active mirror technologies that may reduce the need for costly cryogenic testing.

CALISTO will include both broad-band cameras and wide-band direct-detection spectrometers. For broad-band imaging, the sensitivity of the cold telescope provides very fast mapping speeds, and with the shallow source counts, the 5-meter telescope goes much deeper than Herschel. At 100 microns, a 4000-beam camera can conduct an all-sky survey to the confusion limit, some 450 micro-Jy, corresponding to 3e10 Lsun at z=2. Much deeper imaging is possible at shorter wavelengths.

The bulk of the detector resources will be deployed in a suite of wide-band imaging spectrometer modules, which combine to cover the 30 to 600 micron range. Background-limited spectroscopy with a cold telescope offers potential for million-fold improvements in survey speed, and technical progress in this area is particularly compelling. Each spectrometer will have resolving power~500-1000 across the full sub-band, and ~100-200 spatial resolution elements. We present spectrometer concepts as well as sensitivities and mapping speeds, and dependencies of these scientific performance metrics on aperture size, configuration, and temperature.

9904-179, Session PS5

The FLARE mission: deep and wide-field 1-5um imaging and spectroscopy for the early universe

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FLARE (First Light And Reionization Explorer) is a space mission that will be submitted to ESA (M5 call). Its primary goal (~80% of lifetime) is to identify and study the universe before the end of the reionization at z>6. A secondary objective (~20% of lifetime) is to survey star formation in the Milky Way. FLARE's strategy optimizes the science return: imaging and spectroscopic integral-field observations will be carried out simultaneously on two parallel focal planes and over very wide instantaneous fields of view.

FLARE will help addressing two of ESA's Cosmic Vision themes: a) « How did the universe originate and what is it made of? » and b) « What are the conditions for planet formation and the emergence of life? » and more specifically, « From gas and dust to stars and planets ».

The main goals of FLARE are:

- detect and identify a sample of ~100 candidates primordial galaxies at z > 10.

- The first stars produced and dispersed heavy elements, paving the way for the formation of stellar systems like ours. FLARE's spectrograph will be able to follow the evolution of metallicity at 3< z<10.

- detect and study the emission (including lines) of the first quasars at z>6 to better understand the formation of super-massive black holes.

- FLARE's angular resolution at lambda>2 micrometer, where the extinction is negligible, will observe the formation of stars in the Milky Way from a very wide survey.

To meet FLARE's objectives, the following requirements have been defined: high sensitivity (M1 diameter: 1.8–2.0 m) in the Near-Infrared (1-5 micrometer), relatively high angular resolution (~0.4 arcsec) and above all, wide field of view (~0.2 sq. deg in imaging and 1 sq. arcmin integral-field spectroscopy with 500< R<1000).

The strategy is optimized to build a deep imaging survey over 100–200 sq. deg. down to m_AB = 28 (5 sigma) and an integral-field spectroscopic survey over 1–2 sq. deg, down to a flux 10^-18 erg/cm2/s (5 sigma).

Why do we need a FLARE-like project when JWST, EUCLID, WFIRST and the ELTs will scrutinize the sky? Because only FLARE will combine the following mandatory requirements:

To identify galaxies at z > 10 means:

- we need to search for emissions at lambda > 2-3 micrometers, which

corresponds to the rest-frame 200nm UV emission at 10< z<15.

- We need to be able to confirm their redshift, spectroscopically, which translates into m_AB < 28, even for the E-ELT spectrographs

- These objects are likely to be rare (expected 1 per sq. deg), so, we need at least 100 sq. deg to build a statistically useful sample.

- To reach m_AB = 28 over > 100 sq. deg, we need a 2.0m-class telescope and a dedicated 5-year mission (an observatory shares its time over different projects).

Finally, after JWST, FLARE will work in synergy with SKA, for the re-ionization, ATHENA for the formation and early evolution of quasars and the ELTs for the first galaxies.

9904-180, Session PS5

Optical design of the wide-field, multi-band photometer and integral field spectrograph for the FLARE mission

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FLARE (First Light And Reionization Explorer) is a space mission that will be submitted to ESA (M5 call). Its primary goal is to identify and study the universe before the end of the reionization at z>6.

FLARE will perform imaging and spectroscopic integral-field observations simultaneously on two parallel focal planes and over very wide instantaneous fields of view.

The 2.0m-class telescope has a Korch configuration (3-mirror and a folding) allowing to observe a wide FoV (about 0.4x0.8deg). A focal plane composed of 18 2kx2k IR detectors will be dedicated to the imaging survey in 6 spectral bands (3 detectors per band).

FLARE will also have spectroscopic capability with an integral field spectrograph (IFS) working in the same spectral regions than the imager with an instantaneous field of view of about 1 arcmin2. It is composed of 6 identical integral field units which slices the entrance 2D field in a long 1D-slit. Finally, each slit feeds two spectrographs covering the 2 octaves of the spectral band.

The FoV is arranged in such a way as to allow mapping of >200 square degrees in imagery and >2 square degrees in spectroscopy, covering simultaneously all spectral bands with no moving parts.

In this article we will describe the overall optical design of the FLARE mission.

9904-181, Session PS5

2020 astrophysics decadal large mission concept Ultraviolet/Optical/Infrared (UVOIR) surveyor status and path forward

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In preparation for the 2020 Astrophysics Decadal Survey, an Ultraviolet/Optical Infrared (UVOIR) Surveyor is one of four large mission concepts NASA is studying. Several UVOIR Surveyor variants have been either identified and/or minimally studied to date, including, but not limited to, the 2010 Astrophysics Decadal Survey, "New Worlds New Horizons" which identified the highest priority medium-scale space program priority, a "New Worlds Technology Development Program - to study nearby habitable exoplanets"; the 2013 NASA Visionary Astrophysics 30-Year Roadmap, "Enduring Quests Daring Visions" identified a large UVOIR (LUVOIR) Surveyor; the Associated Universities for Research in Astronomy (AURA) Report, "From Cosmic Births to Living Earths" identified the High Definition Space Telescope (HDST); and several other variants have been studied to varying degrees by industry, NASA field centers, and academia. This broad interest exemplifies the enthusiasm by the community to explore and answer a myriad of compelling science questions in the 2030s, one of the most fundamental humanitarian questions now with our grasp, 'Are We Alone in the Universe?' Assuming current projected funding levels, the mission prioritized by the 2020 Decadal Survey will not receive a programmatic start until nearing the launch of WFIRST-AFTA (~2024-2025), thus, not launching well into the 2030's. In this era, the Hubble Space Telescope (HST), the James Webb Space Telescope (JWST), ESA's Euclid and M4 missions and WFIRST-AFTA will have achieved their exciting science goals and will no longer be in operation. Additionally, ESA's L2 mission, Athena, will have launched in ~2028, and ground-based observatories will have been in operation such as ALMA, ELT, GMT, LBT, LSST, and TMT, to name a few. Mission concepts currently being studied must take into account this scientific and technological context and landscape. Specifically, with the next Decadal Survey identifying the highest priority science (and/or type of mission) in 2019-2020, the identified mission will not get a programmatic start until well into the mid-2020s at the earliest. NASA's Goddard Space Flight Center is providing institutional leadership for the (L)UVOIR Surveyor with a growing multi-institutional team consisting of NASA field centers, academia, industry and potential international partners where the NASA Headquarters appointed Science and Technology Definition Team (STDT) will provide a national community-led fresh and more in-depth consideration of the science objectives, goals, and their relative priorities taking into consideration new and ever-evolving scientific and technology information. Ultimately, the STDT will decide which and how many architectures to study. The (L)UVOIR Surveyor Study Team intends to provide the Decadal Survey and the broad science community with a mission concept with a range of architectural/scaling options associated with different levels of science capability dictated by different starting technology maturities, implementation feasibility, and cost/schedule risks. In the post-HST, post-JWST era, the (L)UVOIR Surveyor is poised to deliver transformative science, as HST has done, across all of astrophysics including Cosmic Origins (COR), Exoplanet Exploration (ExEP), Physics of the Cosmos (PCOS) as well as Solar System planetary science. This paper presents the UVOIR Surveyor mission concept study status, context, and path forward to maximize community involvement.

9904-183, Session PS5

Architecture trades for a habitable-zone exoplanet direct imaging mission

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The recently formed NASA Science and Technology Definition Team for the Habitable-Exoplanet Imaging Mission (HabEx) study has been tasked by NASA with developing a compelling and feasible exoplanet direct imaging concept as part of the 2020 Decadal Survey. Exoplanet and other science capabilities must be traded against cost and risk for a variety of mission architectures to find a concept that meets the standard of both compelling and feasible. Trade areas will include, but are not limited to: direct imaging method, coronagraph type, starshade size and type, telescope size and design, and potential secondary payloads. This paper discusses the architecture trades explored to date, as well as the plan moving forward in the HabEx study.

9904-301, Session 5

NASA Science Technology Definition Team 1: Far-IR Surveyor *(Invited Paper)*

Margaret Meixner, Space Telescope Science Institute (United States)

No Abstract Available

9904-302, Session 5

NASA Science Technology Definition Team 2: HabEx Surveyor *(Invited Paper)*

Bertrand P. Mennesson, Jet Propulsion Lab. (United States)

No Abstract Available

9904-303, Session 5

NASA Science Technology Definition Team 3: LUVOIR *(Invited Paper)*

Kevin C. France, Univ. of Colorado Boulder (United States)

No Abstract Available

9904-304, Session 5

NASA Science Technology Definition Team 4: X-ray Surveyor *(Invited Paper)*

Jessica A. Gaskin, NASA Marshall Space Flight Ctr. (United States)

No Abstract Available

9904-19, Session 6

The Euclid mission design

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Euclid is a space-based optical/near-infrared survey mission of the European Space Agency (ESA) designed to investigate the nature of dark energy, dark matter and gravity by observing their signatures on the geometry of the Universe and on the formation of large structures over cosmological timescales. Euclid will use two main techniques in the detection of the signature of dark matter and energy: Weak gravitational Lensing, which requires the measurement of the shape and photometric redshifts of distant galaxies, and Galaxy Clustering, based on the measurement of the 3-dimensional distribution of galaxies through their spectroscopic redshifts. The mission is scheduled for a launch date in the first half of 2020 and is designed for 6 years of nominal survey operations. The Euclid Spacecraft is composed of a Service Module and a Payload Module. The Service Module comprises all the conventional spacecraft subsystems, the instruments warm electronics units, the sun shield and the solar arrays. In particular the Service Module provides the extremely challenging pointing accuracy required by the scientific objectives. The Payload Module consists of a 1.2 m three-mirror Korsch type telescope and of two instruments, the visible imager and the near-infrared spectro-photometer, both covering a large common field-of-view enabling to survey more than 35% of the entire sky.

Starting from the overall mission requirements, we will describe the spacecraft architectural design and expected performance and will provide a view on the current project status.

9904-20, Session 6

VIS: the visible imager for Euclid

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Euclid-VIS is the large format visible imager for the ESA Euclid space mission in their Cosmic Vision program, scheduled for launch in 2020. Together with the near infrared imaging within the NISP instrument, it forms the basis of the weak lensing measurements of Euclid. VIS will image in a single r+i+z band from 550-900 nm over a field of view of ~0.5 deg2. By combining 4 exposures with a total of 2260 sec, VIS will reach to deeper than V=24.5 (10sigma) for sources with extent ~0.3 arcsec. The image sampling is 0.1 arcsec. VIS will provide deep imaging with a tightly controlled and stable point spread function (PSF) over a wide survey area of 15000 deg2 to measure the cosmic shear from nearly 1.5 billion galaxies to high levels of accuracy, from which the cosmological parameters will be measured. In addition, VIS will also provide a legacy dataset with an unprecedented combination of spatial resolution, depth and area covering most of the extra-Galactic sky. Here we will present the results of the study carried out by the Euclid Consortium during the period up to the Critical Design Review.

9904-21, Session 6

Euclid end-to-end straylight performance assessment

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Euclid is an European Space Agency mission dedicated to the mapping of the geometry of the dark Universe. The mission will investigate the distance-redshift relationship and the evolution of cosmic structures. This is achieved by measuring shapes and redshifts of galaxies and clusters of galaxies out to redshifts ~2, or equivalently to a look 10 billion years back in time. Euclid makes use of two cosmological probes, in a wide survey over the full extragalactic sky : the Weak Gravitational Lensing (WL) and the Baryonic Acoustic Oscillations (BAOs). The WL is a method to map the dark matter and measure dark energy by measuring the apparent distortion of galaxy images by mass inhomogeneities along the line-of-sight. This probe requires extreme image quality thus constraining the optical system imaging quality. The BAOs are wiggle patterns, imprinted in the clustering of galaxies, which provide a standard ruler to measure dark energy and the expansion in the Universe. This experiment involves the determination of the redshifts of galaxies with an accuracy better than 0.1%.

Each probe has a dedicated instrument in the Euclid Payload Module (PLM). The WL experiment involves an instrument (VIS) operating in the visible (500 nm to 900nm) spectral range. The BAO experiment is implemented with the Near Infrared Spectrometer-Photometer (NISP) instrument operating in the near infrared (920 nm to 2000nm) spectral range. Both instruments are fed light by a 1.2 meter-class Korsch type telescope

The extreme constraints imposed on the telescope performances by the probes specifications have driven the definition of stringent straylight requirements for the telescope and both instruments. The straylight induced degradation of the signal-to-noise ratio and light-pollution of spectrum between two close objects in the sky has a direct impact on the number of valid observed objects in the survey. We will present in this paper a brief introduction to the Euclid PLM system. The approach chosen to assess the end-to-end straylight performance and its impact on the scientific outcomes is reported as well. Furthermore we will show the latest assessed performances at system level for both instruments.

9904-22, Session 6

Euclid near infrared spectro photometer (NISP) instrument concept and first test results obtained for different breadbords models at the end of phase C

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The Euclid mission objective is to understand why the expansion of the Universe is accelerating by mapping the geometry of the dark Universe by investigating the distance-redshift relationship and tracing the evolution of cosmic structures. The Euclid project is part of ESA's Cosmic Vision program with its launch planned for 2020.

The NISP (Near Infrared Spectro-Photometer) is one of the two Euclid instruments and is operating in the near-IR spectral region (0.9-2?m) as a photometer and spectrometer. The instrument is composed of:

- a cold (135K) optomechanical subsystem consisting of a SiC structure, an optical assembly (corrector and camera lens), a filter wheel mechanism, a grism wheel mechanism, a calibration unit and a thermal control system

- a detection subsystem based on a mosaic of 16 HAWAII2RG cooled to 95K with their front-end readout electronic cooled to 140K, integrated on a mechanical focal plane structure made with Molybdenum and Aluminum. The detection subsystem is mounted on the optomechanical subsystem structure

- a warm electronic subsystem (280K) composed of a data processing / detector control unit and of an instrument control unit that interfaces with the spacecraft via a 1553 bus for command and control and via Spacewire links for science data

This presentation describes the architecture of the instrument at the end of the phase C (Detailed Design Review), the expected performance, the technological key challenges and preliminary test results obtained for different NISP subsystem breadboards and for the NISP Structural and Thermal model (STM).

9904-23, Session 6

Final tolerancing approach and results for the Euclid NISP instrument

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For the EUCLID-NISP near infra-red instrument's CDR, a refined tolerance analysis has been performed. This takes into account the manufacturing, assembly, spacecraft integration and operational stability of the instrument. The influence of thermal gradients across each of the NISP lenses has been studied to show that this is not causing performance problems. In addition simulations have been done to evaluate the influence of alignment insecurities due to imperfect knowledge of the location of the pupil interface towards the telescope.

These analysis are shown in this paper together with an approach to derive wave-front requirements for optical instrument testing from the encircled energy requirements at NISP system level.

An important part in the analysis is the close relation between tolerance analysis and alignment technology. As the latter is based on multi-zone computer generated holograms (CGH) the properties and accuracies of these elements is also addressed in the paper.

9904-24, Session 6

Optical verification tests of the NISP/ Euclid GRISM qualification model

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Dark matter and dark energy mysteries will be explored by the Euclid ESA M-class space mission which will be launched in 2020. Millions of galaxies will be surveyed through visible imagery and NIR imagery and spectroscopy in order to map the Universe at different evolution stages over the past 10 billion years.

In particular, the massive NIR spectroscopic survey will be done efficiently by the NISP (Near Infrared Spectro-Photometer) instrument thanks to the use of GRISMs (for "Grating pRISMs"). These dispersive optical components allow acquiring the spectra of all galaxies in the imagery field of view at the same time contrary to slit spectroscopy. Four GRISMs mounted on a rotating wheel are used in NISP in order to cover two spectral bands from 0.9 to 1.85μm and to avoid spectra overlapping by rotating the dispersion direction. In addition, the NISP GRISMs integrate three other optical functions: spectral filtering, focus adjustment and spectral wavefront correction. Indeed, a multilayer filter selecting the spectral band passes (0.9-1.3μm and 1.25-1.85μm) is deposited on the curved first face of the prism (kind of lens) and the grooves of the grating made on the other prism face are not straight and parallel allowing spectral aberrations corrections. Therefore, these optical elements are very challenging to manufacture (3 industrial partners work on a single optical component) and to test before integration into NISP.

In this paper, we present the optical verification tests done on the GRISM Engineering Qualification Model at each step of the manufacturing process: (1) grating on a parallel plate, (2) prism with curved face and (3) filter deposition. First, we verify the groove profile and transmitted efficiency specified to be more than 65% on a wide spectral band (1.25-1.85μm) in order one. Second, we measure the grating and the filter surfaces error specified to be respectively less than 30nm RMS without focus. Finally, the total transmitted efficiency, the out of band rejection and the wavefront error including focus are measured after the filter manufacturing.

9904-25, Session 6

Latency model of Euclid H2RG IR detectors for the NISP instrument of the Euclid mission

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Euclid is an ESA mission to map the geometry of the dark Universe with a planned launch date in 2020. The Near-Infrared photo-spectrometer instrument (NISP) contains a large focal plane assembly of 16 Teledyne H2RG detectors. CPPM is in charge of the final characterization of the flight H2RG infrared detectors . The knowledge of detectors performances is crucial to the instrument calibration and requires a thorough characterization effort. Engineering grade Euclid-like detectors are currently being tested at CPPM to validate associated characterization test plan. One major goal for this activity is to prepare future analyses and corrections needed for precise calibration and performance control after flight. One main issue is to define a test plan to control and correct if needed the persistence effects of these detectors throughout the mission. A characterization plan is under study to measure and establish a reliable model of the in-flight H2RG detector persistence signal that

can be used to predict and correct the flight data. An initial study of the persistence behavior of those detectors will be presented and a model will be proposed and data analysis described, based on representative engineering data. In the next phase, flight detectors, selected and tested by NASA, will be received and fully characterized for persistence effect at CPPM before their integration.

9904-26, Session 7

The Primordial Inflation Explorer (PIXIE)

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The Primordial Inflation Explorer is an Explorer-class mission to measure the gravity-wave signature of primordial inflation through its distinctive imprint on the linear polarization of the cosmic microwave background. PIXIE uses an innovative optical design to achieve background-limited sensitivity in 400 spectral channels spanning 2.5 decades in frequency from 30 GHz to 6 THz (1 cm to 50 micron wavelength). Multi-moded non-imaging optics feed a polarizing Fourier Transform Spectrometer to produce a set of interference fringes, proportional to the difference spectrum between orthogonal linear polarizations from the two input beams. Multiple levels of symmetry and signal modulation combine to reduce systematic errors to negligible levels. PIXIE will map the full sky in Stokes I, Q, and U parameters with angular resolution 2.6 deg and sensitivity 0.2 μK per 1 deg square pixel. The principal science goal is the detection and characterization of linear polarization from an inflationary epoch in the early universe, with tensor-to-scalar ratio r < 10-3 at 5 standard deviations. The PIXIE mission complements anticipated ground-based polarization measurements such as CMB-S4, providing a cosmic-variance-limited determination of the E-mode signal to measure the optical depth, constrain models of reionization, and improve limits on the neutrino mass. In addition, PIXIE will measure the absolute frequency spectrum to characterize deviations from a blackbody spectrum with sensitivity 3 orders of magnitude beyond the seminal COBE/FIRAS limits. The sky cannot be black at this level; the expected results will constrain physical processes ranging from inflation to the nature of the first stars and the physical conditions within the interstellar medium of the Galaxy. We describe the PIXIE instrument and mission architecture required to measure the CMB to the limits imposed by astrophysical foregrounds.

9904-27, Session 7

LiteBIRD: lite satellite for the study of B-mode polarization and inflation from cosmic microwave background radiation detection

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LiteBIRD is a next generation satellite for the detection of the B-mode polarization of the Cosmic Microwave Background (CMB) to measure the tensor-to-scaler ratio with the sensitivity of 0.002 at the 95% confidence level, offering us the test of the major large-single-field slow-roll inflation models.

LiteBIRD is planned to conduct an all sky survey at the sun-earth 2nd Lagrange point (L2) with an angular resolution of about 0.5 degrees to measure the B-mode power spectrum in the range of ell=2 to 200 in its three years of operation.

The measurement system contains an optical system, focal plane detector arrays and polarization modulators. The optical system contains two telescopes: one makes use of the modified crossed-Dragone telescope that offers the telecentric field of view of 10 x 20 degrees in the frequency range of 40 to 235 GHz, called the Low Frequency Telescope (LFT), and another is a refractor telescope operating from 280 to 402 GHz, called the High Frequency Telescope (HFT). The two focal planes of the LFT and the HFT are kept at 100 mK with an adiabatic demagnetization refrigerator (ADR). On each focal plane, an array of superconducting detectors is located. The 2276 superconducting detectors in total provide a sensitivity of 1.7 uKarcmin which includes the degradations due to the production yield, ADR duty cycle and cosmic ray glitch removal. The superconducting detector candidates are Transition Edge Sensors (TES) and Microwave Kinetic Inductance Detector (MKID). Each telescope has a continuous rotating Half Wave Plate (HWP) that modulates the polarization of the incoming photons. The separation of the two telescopes relaxes the requirements imposed on the HWP specification in terms of the bandwidth and anti-reflection.

The LiteBIRD mission is being designed with respect to the specification of the satellite, the data transfer to the ground and the mission operation concept. One of the items critical to determine the satellite design is the scan strategy. The baseline scan is a combination of the precession and the spin rotation. The precession angle with respect to the sun-earth axis is 65 degrees with the rate of about 90 minutes per revolution, and the boresight rotates around the spinning axis with an angle of 30 degrees. The revolution rate of the spin is 0.1rpm. In case of the mulfunction of the HWP, the spin rate can be increased to 0.3 rpm. The estimated data rate is about 400 kbps with the HWP. The data are transferred to the ground stations using the X-band telemetry.

The LiteBIRD mission has been down-selected as a candidate of the JAXA strategic large missions and is in the transition to the Phase-A1 study. During Phase-A1, the satellite specification will be fixed and reviewed to proceed to Phase-A2. The LiteBIRD US team's proposal for the NASA Missions of Opportunity has also been down-selected for the Phase-A study to design the focal plane detectors and the ADR as well as the data analyses. The target launch year is in early 2020s.

9904-28, Session 7

Scientific overview of the Galaxy Evolution Spectroscopic Explorer (GESE)

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GESE is a multi-object slit spectrograph designed to help understand galaxy evolution in a critical era in the history of the universe: the period when star formation peaked and started its decline which continues to the present day. To isolate the various processes driving the evolution of these galaxies, GESE will obtain rest-frame far-UV spectra of >50,000 galaxies at redshifts, z~1-2. To obtain such a large number of spectra, multiplexing over a wide field is an absolute necessity. A digital micro-mirror device (DMD) offers an innovative solution to this challenge. By forming small "slits" around target galaxies in the field, a DMD enables spectroscopy of hundreds of sources in a single exposure while eliminating overlapping spectra of other sources and blocking unwanted background like zodiacal light. The actual multiplexing factor in the GESP case is a function of the field of view and the limiting sensitivity of the spectrograph. We find that a 1m-class space telescope combined with a custom orbit enabling a high fraction of time on target and uninterrupted long exposures (~10 hr) are optimal for this spectroscopic survey program.

9904-29, Session 8

Main results of the PICARD mission

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PICARD is a mission devoted to solar variability observation, through imagery and radiometric measurements, with the goal to provide data for scientific investigation first in the area of solar physics, and second in the assessment of the influence of the solar variability on the Earth climate variability. PICARD contains a double program with in-space and on-ground measurements. The PICARD spacecraft was launched on June 15, 2010, commissioned in-flight in October of the same year, and was retired in April 2014. PICARD ground-based is functional since May 2011, and is still operational today. We shall give an overview of the PICARD instrumentation. New estimates of the absolute values of the total solar irradiance, of the solar spectral irradiance at typical wavelengths, and of the solar oblateness will be given. We will also report about helioseismic studies. Finally, we will present our current results about solar radius variations after six years of solar observations.

9904-30, Session 8

Geometrical distortion calibration of the stereo camera for the BepiColombo mission to mercury

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The ESA-JAXA mission BepiColombo, to be launched in 2017, is dedicated to the observation of Mercury, the innermost planet of the Solar System. Simbiosys is its remote sensing suite, which consists of three instruments: the High Resolution Imaging Channel (HRIC), the Visual and Infrared Hyperspectral Imager (VIHI), and the Stereo Camera (STC). The latter will provide the global three dimensional reconstruction of the Mercury surface, and it represents the first push-frame stereo camera on board of an astronomical satellite.

Based on a new design telescope, STC combines the advantages of a compact single detector to the convenience of a double direction acquisition system that permits to minimize mass and volume and allows push-frame imaging. The camera common sensor is divided in six portions: four are covered with suitable filters, the others, one looking forward and one backwards with respect to nadir direction, are covered with a panchromatic filter and supply stereo image pairs of the planet surface. The basic STC scientific requirements are to reconstruct the Mercury surface with a vertical accuracy better than 80 m and an imaging grid size of 65 m at periherm.

Scope of this work is to present the on-ground geometric calibration pipeline for a so unique instrument. Classical push-broom camera present a simpler distortion definition. STC offers on the other side all the advantages of a push-frame instrument but a delicate configuration considering the photogrammetric purposes of STC and the harsh environment where it will work.

The selected STC off-axis configuration obliges to change the classical definition of the distortion map, this is a delicate argument in the photogrammetric field where the stereo matching process needs pinhole undistorted or orthorectified images as first input of the DTM processor pipeline.

Additional considerations are connected to the detector, a Si-Pin hybrid CMOS, which is characterized by a high fixed pattern noise. This had a great impact in pre-calibration phases compelling to use a not common approach to the definition of the spot centroids in the distortion calibration process.

Thermic variability is another issue worth to be analysed, as also shown by other missions (as NASA MESSENGER) on Mercury; thus, different temperature effects on the distortion model for both the panchromatic channels of the instrument have been taken in account.

A specific set-up has been realized for the geometrical distortion calibration in cleanroom It is composed by a lens collimator, and a flat steering mirror mounted on a double axis rotational stage to redirect the collimated light beam with the desired inclination toward STC input aperture. A second rotational stage is able to handle the thermal-vacuum camera, containing the STC instrument, in order to select one STC sub-channel or the other.

This work presents the results obtained by the distortion calibration of STC, for three different temperatures. These results are then used to define the corresponding distortion models of the camera.

9904-31, Session 8

Development of compact metal-mirror image slicer unit for optical telescope of the SOLAR-C mission

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The SOLAR-C is a Japan-led international solar mission designed to investigate the magnetic activities of the Sun, focusing on the study in heating and dynamical phenomena of the chromosphere and corona. For these purposes, SOLAR-C will carry three dedicated instruments; the Solar UV-Vis-IR Telescope (SUVIT), the EUV Spectroscopic Telescope and the High Resolution Coronal Imager, to jointly observe the entire visible solar atmosphere with essentially the same high spatial resolution (0.1-0.3 arcsec), performing high resolution spectroscopic measurements over all atmospheric regions and spectro-polarimetric measurements from the photosphere through the upper chromosphere. The SUVIT is a meter-class telescope in order to grasp sufficient spatial resolution and S/N ratios. The SUVIT spectro-polarimeter for spectral lines such as Fe I 525 nm, Ca II 854 nm, and He I 1083 nm should be equipped with a powerful integral field unit to grasp the rapidly changing chromospheric phenomena with about 10 arcsec x 10 arcsec field-of-view. Integral field spectroscopy is a two dimensional spectroscopy, providing spectra simultaneously for each spatial direction of an extended two-dimensional field. From the view point of a high efficiency spectroscopy, a wide wavelength coverage and a precision spectro-polarimetry, the mirror image slicer is the best option. The role of the image slicer unit (IFU) is to couple between the telescope and the spectrograph by reformatting optically a rectangular field into a quasi-continuous pseudo-slit located at the entrance focal plane of the spectrograph. The mirror image slicers are presently limited either by their risk in the case of glass polishing techniques or by their performances when constituted by metallic mirrors. We present an innovative optical design for IFU and manufacturing method to attain high performances of micro image slicer; accurate roughness, sharp edges, surface form, etc., using a novel technique developed by Canon. The IFU consists of image slicer of 45 arrayed 30-micron-thick metal mirrors and a pseudo pupil mirror array for three pseudo-slits, providing possible optical configuration for a coexistence with a conventional single-slit spectrograph. We confirmed that the surface roughness, the surface accuracy and the tilt errors of all surfaces of a prototype pupil mirror are less than 1.3 nm rms, 59 nm PV and 4.6 arcsec, respectively.?The IFU mirrors were deposited by a protected silver coating for high reflectivity. The IFU need to be equipped with a field lens at the slit plane to feed telecentric beam into

the spectrograph. We describe the optical design, performance of IFU and space qualification of the silver coating for SOLAR-C SUVIT.

9904-32, Session 9

Wide-Field InfraRed Survey Telescope (WFIRST) slitless spectrometer: design, prototype, and status

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The slitless spectrometer plays an important role in the WFIRST/AFTA mission for the survey of emission-line galaxies. This will be an unprecedented very wide field, HST quality 3D survey of emission line galaxies. The concept of the compound grism has been presented previously. This presentation briefly discusses the challenges and solutions of the optical design, and recent specification updates, as well as a brief comparison between the prototype and the latest design. However, the emphasis of this presentation is the progress of the grism prototype: the fabrication and test of the complicated diffractive optical elements and powered prism, as well as grism assembly design and alignment. Especially how to use different tools and methods, such as phase shift interferometry and Point Diffraction Interferometry (PDI), and phase retrieval, to complete the element and assembly tests. The paper also discusses the cryogenic test plan, to be performed after the ambient test on the prototype grism assembly. Finally we briefly touch how the test results will be used to improve the flight spectrometer design during phase A.

9904-33, Session 9

Canadian contributions study for the WFIRST coronagraph instrument

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WFIRST-AFTA is the top American mission that was identified in the New World, New Horizon survey. This mission will provide insights in key modern astrophysical questions through a high-latitude survey to study dark energy, a galactic bulge survey to detect microlensing events for large orbit and free-floating companion detection, coronagraphic observations of cold planets and of proto-planetary discs and a Guest Observer Program. This will be done with two main instruments, a wide field imager and a coronagraphic instrument. There is a great interest in having an international collaboration in this mission that addresses some of the deep questions identified in the Canadian LRP2010. In this context, the Canadian Space Agency has awarded two contracts to study a Canadian participation in the mission, one related to each instrument. This paper reports the results of the study for the coronagraphic instrument, its potential impact on the Canadian science and on the Canadian industry.

9904-34, Session 9

The WFIRST coronagraph instrument: from technology advancement to flight design

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The Wide Field InfraRed Survey Telescope (WFIRST) is a NASA space observatory that has been designed to probe dark energy, to carry out wide-field near infrared (NIR) surveys, and to discover and characterize extrasolar planets (hereafter exoplanets) in the visible spectrum. WFIRST observatory will make use of an existing 2.4-m aperture Astrophysics Focused Telescope Asset (AFTA) and will advance what is currently possible in exoplanet spectral characterization and imaging. The AFTA coronagraph also matures direct imaging technologies to high TRL for an Exo-Earth Imager in the next decade. The coronagraph will carry out direct imaging and detailed visible spectroscopy of a sample of exoplanets. The coronagraph will be able to detect and characterize cold Jupiters, mini-Neptunes, and possibly super-Earths and for the first time directly image planets analogous to those in our solar system. This spectroscopic characterization will reveal the atmospheric composition of these planets and will be used to search for spectral signatures of life. In addition, the coronagraph will be used to characterize debris disks in and around planetary orbits—an important tool that can be used to improve our understanding of planet formation.

The coronagraph Design Reference Mission (DRM) optical design is based on the highly successful High Contrast Imaging Testbed (HCIT), with modifications to accommodate the AFTA telescope design, service-ability, volume constraints, and the addition of an Integral Field Spectrograph (IFS). In order to optimally satisfy the three science objectives of planet imaging, planet spectral characterization and dust debris imaging, the coronagraph is designed to operate in two different modes: Hybrid Lyot Coronagraph or Shaped Pupil Coronagraph. Active mechanisms change pupil masks, focal plane masks, Lyot masks, and bandpass filters to shift between modes. A single optical beam train can thus operate alternatively as two different coronagraph architectures.

In order to adequately form images and collect spectra of exoplanets, it is necessary to suppress the starlight to a contrast of order 10?9 for cold Jupiters, mini-Neptunes, and super-Earths. The coronagraph accomplishes this by using (1) a series of masks to reject starlight, to block diffracted light, and to reduce starlight speckles, and (2) an adaptive optics system, employing a pair of deformable mirrors (DMs) in order to eliminate residual speckles due to optical imperfections in the entire optical beamtrain. When carrying out planet discovery, photometry, and disk imaging, the coronagraph relays an image of the high-contrast “dark hole” onto the imaging camera. A stationary polarizing beam splitter in front of the imaging camera separates the dark hole image into two orthogonal polarizations, whose two resulting images fill a small rectangular area of the detector. When taking planetary spectra, by contrast, the Integral Field Spectrograph (IFS) images a regular grid of spectrally dispersed PSFs onto the detector. The very low expected photon count requires sub-electron read noise, dark current, and clock-induced charge (CIC) to carry out planet spectroscopy.

9904-35, Session 9

WFIRST-AFTA coronagraph starlight suppression technology progress

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NASA's WFIRST-AFTA mission will use an existing 2.4 meter diameter telescope and include an active, high-contrast stellar coronagraph instrument that will be capable of directly imaging and spectrally characterizing exoplanets and circumstellar disks in reflected starlight. NASA has selected the Occulting Mask Coronagraph (OMC) that combines two well-known starlight suppression approaches, Shaped Pupil and Hybrid Lyot, as the primary design for WFIRST, and the Phase-Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC) as the backup design.

Since early 2014, both the primary and backup coronagraph technologies have been aggressively matured to demonstrate (1) the performance and space flight readiness of the key starlight suppression components designed for WFIRST and (2) the ability of the coronagraph to achieve the required level of starlight suppression with the WFIRST-AFTA telescope "as is," including its obscured pupil, expected thermal drifts, and the observatory pointing jitter. NASA's timeline calls for bringing the system level coronagraph to Technology Readiness Level (TRL) 5 in 2016, with 9 independently reviewed milestones to track the technology progress along the way. The first 6 of these 9 WFIRST coronagraph milestones were met on schedule in 2014 and 2015. These milestones have demonstrated that:

1. The novel occulting and pupil apodization masks for starlight suppression with WFIRST-AFTA telescope can be successfully fabricated for all primary and backup starlight suppression approaches

2. The coronagraph has demonstrated repeatable convergence to a high level of starlight suppression in a vacuum testbed with WFIRST telescope pupil. The testbed results show consistent convergence to better than 10-8 average contrast in 10% broadband light between 3 and 9 ?/D for both Hybrid Lyot and Shaped Pupil OMC modes.

3. Operation of the low order wavefront sensing and control subsystem that uses the starlight rejected by the coronagraph to measure and correct observatory pointing jitter and thermal drifts to the level needed to observe the exoplanet targets.

During the course of 2016, the fidelity of the testbed demonstrations will increase further, with the new testbed design closely following the flight instrument, and a sophisticated optical telescope assembly simulator to inject the wavefront disturbances expected on orbit into the coronagraph. All these accomplishments and up-to-date WFIRST coronagraph technology progress will be summarized.

9904-36, Session 9

Exoplanet and disk detection with the WFIRST coronagraph

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The Coronagraph Instrument (CGI) on the planned WFIRST mission will detect and characterize reflected-light images and spectra from exoplanets and dust disks around nearby stars. The CGI will operate in several visible wavelength bands, and will be able to take polarized-light images of exoplanets and disks, as well as obtaining spectra. Recent advances in the science and technology of the CGI are improving our ability to forecast the sensitivity and limits of this instrument. This paper presents the current status of our expectation for science results, including recent advances in our understanding of targets, backgrounds, and instrument and detector performance.

9904-37, Session 10

Managing the optical wavefront for high contrast exoplanet imaging with the WFIRST-AFTA coronagraph

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The prospect of extreme high contrast astronomical imaging from space has inspired developments of new coronagraph methods for exoplanet imaging and spectroscopy. However, the requisite contrast, at levels of a billion to one or better for the direct imaging of cool mature exoplanets in reflected visible starlight, leads to challenging new requirements on the stability and control of the optical wavefront at levels currently beyond the reach of ground based telescopes. We review the designs, laboratory validations, and science prospects for direct imaging and spectroscopic characterization of exoplanet systems with an actively corrected Lyot coronagraph. We review exoplanet science performance predicted for NASA's WFIRST-AFTA coronagraph. Together with a pair of deformable mirrors for optical wavefront control, the Lyot coronagraph creates high contrast dark fields of view extending to angular separations within 0.1 arcsec from the central star at visible wavelengths. Performance metrics are presented, including image contrast and spectral bandwidth, and laboratory validation experience.

9904-38, Session 10

Low-order wavefront sensing and control for WFIRST coronagraph

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NASA's WFIRST Coronagraph will be capable of directly imaging and spectrally characterizing giant exoplanets similar to Neptune and Jupiter, and possibly even super-Earths, around nearby stars. To maintain the required performance of WFIRST Coronagraph in a realistic space environment, a Low Order Wavefront Sensing and Control (LOWFS/C) subsystem is necessary. The LOWFS/C will use the rejected stellar light from coronagraph to sense and suppress the telescope line-of-sight (LoS) pointing drift and jitter as well as low order wavefront drifts due to the changes in thermal loading of the telescope and the rest of the observatory. The LOWFS/C uses a Zernike wavefront sensor (ZWFS)

with the phase shifting disk combined with the stellar light rejecting occulting mask, a key concept to minimize the non-common path error. For wavefront corrections, WFIRST LOWFS/C uses a dedicated fast steering mirror (FSM) for line-of-sight correction, a focusing mirror for focus drift correction, and one the two deformable mirrors (DM) for other low order wavefront modes correction. Detailed diffraction modeling and analysis have been done to evaluate the performance of LOWFS/C for WFIRST Coronagraph. Developed as a part of the Dynamic High Contrast Imaging Testbed (DHCIT) for the WFIRST technology development, the LOWFS/C subsystem also consists of an Optical Telescope Assembly (OTA) Simulator to generate the realistic wavefront error and LoS drift and jitter from WFIRST telescope's vibration and thermal changes. The entire LOWFS/C subsystem has been integrated, calibrated, and tested in a dedicated LOWFS/C testbed. The testbed results have shown that the Zernike WFS have line-of-sight tilt sensitivity better than 0.2 milli-arcsec and closed-loop post correction residual better than 0.4 milli-arcsec with the presence of the WFIRST-AFTA like LoS drift and jitter (14 milli-arcsec). After the stand alone test on the LOWFS/C testbed the LOWFS/C subsystem including OTA Simulator has been integrated into the DHCIT. In this paper we will describe the LOWFS/C subsystem and present the LOWFS/C performance testbed results as well as the preliminary results of LOWFS/C subsystem working together with the coronagraph on the DHCIT.

9904-39, Session 10

Closing the contrast gap between testbed and model prediction with WFIRST-AFTA shaped pupil coronagraph

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JPL has recently passed an important milestone in its technology development for a proposed NASA WFIRST-AFTA mission: demonstration of a better than 1e^-8 contrast over broad bandwidth (10%) on both shaped pupil coronagraph and hybrid Lyot coronagraph testbeds with AFTA telescope optics. Challenges remain, however, in the technology readiness for the proposed mission. One such is the discrepancy between the achieved contrast on testbed and that from model prediction. To close the contrast gap between model prediction and actual testbed performance, a series of testbed diagnosis and modeling activity were planned and some have been carried out. A very effective approach we find is to compare and analyze the measured testbed Jacobian matrix and a model-based control Jacobian that is used to control image plane speckle (in a high contrast coronagraph that uses electric field conjugation algorithm for wavefront sensing and control, Jacobian is the image plane complex electric field sensitivity to a pupil plane DM actuator poke). The difference between these two is the error in the control Jacobian (including both amplitude and phase). We show that the level and nature of this error closely explains the contrast performance discrepancy observed in terms of contrast floor and contrast convergence speed, when the error is inserted into a simulation model for coronagraph contrast prediction. This offers a new perspective and represents a big step forward in the model validation for better prediction and understanding of testbed contrast performance limit. It also provides clues to the possible sources for mismatch and points direction for potential testbed improvement. Further simulation on Jacobian error source offers more specific sources for the apparent mismatch. Modifications to both testbed control model as well as prediction model are being implemented.

9904-40, Session 10

Hybrid Lyot coronagraph for WFIRST-AFTA: occulter fabrication and high contrast broadband testbed demonstration

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Hybrid Lyot Coronagraph (HLC) is one of the two operating modes of the WFIRST-AFTA coronagraph instrument. It produces starlight suppression over full 360 degrees annular region and thus is particularly suitable for discovery of unknown exoplanets. Since being selected by National Aeronautics and Space Administration (NASA) in December 2013, the coronagraph technology is being matured to Technology Readiness Level (TRL) 5 by September 2016. We present the up-to-date progress of HLC key component fabrication and testbed demonstrations with the WFIRST-AFTA pupil. Circular HLC occulter masks consisting of metal and dielectric layers have been fabricated and characterized. Wavefront control using two deformable mirrors is successfully demonstrated in a vacuum testbed with 10% broadband light centered at 550 nm. As a result, we obtain repeatable convergence below 1E-8 mean contrast in the 360 degrees dark hole with working angle between 3 ?/D and 9 ?/D. We present the hardware and software used in the testbed, the results and the associated analysis, including preliminary estimates of exoplanet yield consistent with the results obtained in the testbed.

9904-41, Session 11

The LATT way towards large active primaries for space telescopes

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The Large Aperture Telescope Technology (LATT) goes beyond the current paradigm of future space telescopes, based on a deformable mirror in the pupil relay.

Through the LATT project we demonstrated the concept of a low-weight active primary mirror, whose working principle and control strategy benefit from two decades of advances in adaptive optics for ground-based telescopes. We developed a forty centimeter spherical mirror prototype, with an areal density lower than 22kg/m2, controlled through contactless voice coil actuators with co-located capacitive position sensors. The prototype was subjected to thermo-vacuum, vibration and optical tests, pushing its technical readiness toward level 5.

In this paper we present the background and the outcomes of the LATT

activities under ESA contract, exploring the concept of a lightweight active primary mirror for space telescopes. Active primaries will open the way to very large segmented apertures, actively shaped, which can be lightweight, deployable and accurately phased once in flight.

9904-42, Session 11

Telescope polarization and image quality: uncompensated polarization aberrations

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Uncompensated polarization aberrations limit radiometric precision, reduce coronagraph contrast, modify recorded spectra and limit precision astrometry. Optical systems for astronomy are designed, optimized and built using scalar diffraction and geometric aberration theory and hardware. However current astronomical science measurement objectives require high quality imaging only possible using the analysis tools of vector diffraction, partial coherence, non-linear image processing and polarization aberration analysis along with their associated hardware devices and software image processing methods.

This paper presents results of modeling a “typical” telescope for vector diffraction, monochromatic & polychromatic polarization-aberrations and discusses their effects on coronagraph contrast and allowable filter bandwidth, field-dependent PSF asymmetry, transmittance, field of view and calibration. If we are to achieve system performance at these levels: 1. <100nm wavelength, 2. <1% exit pupil spatial uniformity, 3. <0.02% residual polarizance and 4. Maximum phase and amplitude transmittance, over scientifically interesting FOV’s, then polarization aberrations must to be considered in the design and fabrication of modern astronomical telescopes and instruments.

We show that the performance of the WFIRST-coronagraph system will be limited by uncorrected polarization aberrations and discuss several polarization aberration mitigation approaches.

9904-43, Session 11

Innovative focal plane design for large space telescopes

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In the frame of a CNES R&T project, LAM and CNES are studying the reorganization of focal plane on scan-drift telescopes for VIS/IR applications. Indeed, physical dimensions of future large scan drift space telescopes are increased leading more complex, massive and bulky systems. In order to reach higher image quality and sensitivity keeping a large field of view, the use of homothetic imaging systems is prohibitive. We present an innovative approach based on the Integral Field Units already used on ground based instrumentation. The idea is to reimage a linear field of view on a 2D detector array, by use of a set of segmenting mirrors. For infrared instruments used in space applications, the volume of the cryostat used to cool down the detectors array is a dimensioning parameter for the lifetime of the mission. This new technology would allow a significant reduction of the size of such space systems. We present studies done so far on optical system design and the first technological demonstrator we developed.

9904-44, Session 11

The CaSSIS imager and FPA: integration and optical performance overview

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The CaSSIS camera (Colour and Stereo Surface Imaging System) is the high-resolution color and stereoscopic imager of the instrument payload on board of the ESA space mission EXOMARS 2016 TGO (Trace Gas Orbiter).

CaSSIS will provide detailed observations to investigate dynamic processes (e.g. sublimation, erosional processes, volcanism) on the Mars surface with a spatial scale of 4.6 m per pixel from an altitude of 400 km (horizontal scale). The CaSSIS stereo capability is based on rotation mechanism that allows the camera to look 10 degrees ahead and 10 degrees behind the spacecraft track acquiring a stereo pair of images of the same area during the same orbit. The stereoscopic reconstruction enables a vertical resolution of about six meters (vertical scale).

The CaSSIS optical system is based on a TMA telescope (Three Mirrors Anastigmatic configuration) with a 4th powered folding mirror compacting the CFRP (Carbon Fiber Reinforced Polymer) structure. The camera EPD (Entrance Pupil Diameter) is 135 mm, and the focal length is 880 mm, giving an F# 6.5; the wavelength range covered by the instrument is 400-1100 nm. The optical system is designed with distortion less than 2% and a worst case MTF (Modulation Transfer Function) of 0.3 at the detector Nyquist spatial frequency (i.e. 50 lp/mm).

The Focal Plane Assembly (FPA) detector is a spare component of the Simbio Sys instrument of the Italian Space Agency (ASI). Simbio Sys will fly on ESA’s Bepi Colombo mission to Mercury. The detector developed by Raytheon Vision Systems is a 2kx2k hybrid Si-PIN array with a 10 ?m pixel allows snapshot operation at a read-out rate of 5 MPixel/s with 14 bit resolution. CaSSIS will operate in push-frame mode with a filter strip assembly (FSA) selecting 4 color bands, integrated by Selex ES (under TAS-I responsibility) directly above the detector sensitive area.

The University of Bern was in charge of the full instrument integration as well as the characterization of the focal plane. The paper will present an overview of CaSSIS and the optical performance of the telescope and FPA. The preliminary results of the on-ground calibration campaign will be described in detail.

9904-184, Session PS6

Correcting for the effects of pupil discontinuities with the ACAD method

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The current generation of ground-based coronagraphic instruments uses deformable mirrors to correct for phase errors and to improve contrast levels at small angular separations. However, as wavefront control techniques improve, more complex telescope pupil geometries (support structures, segmentation) will be a limiting factor for the next generation

of coronagraphic instruments. The Active Compensation of Aperture Discontinuities (ACAD) method is based on the resolution of the non-linear Monge-Ampere two-mirror propagation equations to calculate the deformable mirror shape solutions that cancel the effects of discontinuities in the pupil for any pupil geometry and any coronagraph used. Taking advantage of the fact that most future coronagraphic instruments will include two deformable mirrors, this technique will allow the use of any coronagraph designed for continuous apertures with complex segmented apertures and secondary mirror support structures, with high throughput, and flexibility to adapt to changing pupil geometry, e.g. in case of segment failure or maintenance of the segments. We here present a study on several pupil geometries (segmented Large UV optical IR –LUVOIR– telescope, off-axis segmented telescope, WFIRST, ELTs) for which we obtained high contrast levels with several deformable mirror setups (size, number of actuators, separation between them), coronagraphs (Vortex, APLC) and spectral bandwidths. However, because contrast level and separation are not the only metrics to maximize the scientific return of an instrument, we also included in this study the influence of these deformable mirror shapes on the throughput of the instrument, sensitivity to pointing jitters and outer and inner working angles.

9904-185, Session PS6

A four mirror anastigmat collimator design for optical payload calibration

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We present here a four mirror anastigmatic optical collimator design intended for the calibration of an earth observation satellite instrument. Specifically the collimator is to be applied to the ground based calibration of the Sentinel-4/UVN instrument. This imaging spectrometer instrument is expected to be deployed in 2019 in a geostationary orbit and will make spatially resolved spectroscopic measurements of atmospheric contaminants.

The purpose of the collimator is to provide collimated light within the two instrument passbands in the UV-VIS (305 – 500 nm) and the NIR (750 – 775 nm). Moreover, that collimated light will be derived from a variety of slit like objects located at the input focal (object) plane of the collimator which is uniformly illuminated by a number of light sources. The collimator must relay these objects with exceptionally high fidelity. To this end, the wavefront error of the collimator should be less than 20 nm rms across the collimator field of view. This field is determined by the largest object which is a large rectangular slit, 4.4° x 0.25°. Other important considerations affecting the optical design are the requirements for input telecentricity and the size (85 mm) and location (2500 mm 'back focal distance') of the exit pupil.

The requirement for diffraction limited performance across a very wide spectral range suggests the use of a mirror design. Since defocus forms part of the wavefront error requirement, the design must be substantially achromatic. Correction of the five primary Gauss-Seidel aberrations would, at first sight, require the use of three mirrors. This forms the basis of the well-known Three Mirror Anastigmat (TMA) design. However, in this case an additional constraint is imposed – that of telecentricity. Therefore, in this design an additional mirror is introduced to provide an extra degree of freedom. As with the TMA, this four mirror anastigmat design uses off axis conics.

Extensive tolerancing analysis of the design has been carried out and is reported here. For the majority of the mirrors, the form error must be less than 10 nm rms. Whilst this is within manufacturing tolerances, it does pose a significant challenge. The tolerancing and sensitivity analysis described also impacts the system alignment strategy which is also outlined here. Great attention has also been paid to the mechanical design and, in particular, the mounting of the individual mirrors. Significant mounting distortions must be avoided in any event and the design of suitable mirror mounts is described in some detail. The impact of thermal distortions is also described.

As a calibration source for a spectroscopic instrument, an important part of the calibration exercise is the characterisation of stray light. Therefore, the straylight produced by this collimator design must be characterised in detail and minimised as far as possible. Results of a non-sequential straylight model are presented in detail and strategies for minimising scattered light are discussed.

9904-186, Session PS6

Xenon arc lamp spectral radiance modelling for satellite instrument calibration

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Precise radiometric measurements play a central role in many areas of astronomical and terrestrial observation. We focus on the use of continuum light sources in the absolute radiometric calibration of detectors in an imaging spectrometer for space applications. The application, in this instance, revolves around the ground based calibration of the Sentinel-4/UVN instrument. This imaging spectrometer instrument is expected to be deployed in 2019 and will make spatially resolved spectroscopic measurements of atmospheric chemistry.

Of key importance to the fidelity of these measurements is the ground based calibration campaign. When deployed, the instrument will compare the spectral radiance of the of the Earth's atmosphere with the (variable) solar irradiance. These measurements will be made using two separate paths, the 'Earth Port' and the 'Sun Port'. Knowledge of the relative sensitivities of these two optical paths is essential to the function of the instrument. A major part of this calibration process will involve a comparison of the ratio of these two sensitivities using a highly stable continuum light source. This light source will cover the two spectral ranges of the instrument, namely the UV-VIS (305-500 nm) and the NIR (750-775 nm). A short arc xenon lamp is to be the primary source in this calibration process.

Xenon short arc lamps provide highly intense and efficient continuum illumination in a range extending from the ultra-violet to the infra-red and their spectrum is well matched to this specific application. Despite their widespread commercial use, certain aspects of their performance are not well documented in the literature. One of the important requirements in this calibration application is the delivery of highly uniform, collimated illumination at high radiance. In the design of optical modules to deliver this uniform illumination, it cannot be assumed that the xenon arc is a point source; the spatial distribution of the radiance must be characterised to assist with optical design process. We present here careful measurements that thoroughly characterise the spatial distribution of the spectral radiance of a 1000W xenon lamp. These results are analysed in order to describe the spatial distribution with a simple mathematical model.

Temporal stability is another exceptionally important requirement in the calibration process. As such, the paper also describes strategies to re-inforce the temporal stability of the lamp output by means of a closed loop attenuation scheme and current control. Although the use of current control and output stability is extensively covered in the literature, there is one specific aspect that has received little attention. The xenon arc spectrum, whilst, for the most part a continuum, does contain a number of highly broadened atomic line features, mostly from Xe I and Xe II. The variation in output of these lines with lamp current is different when compared to that of the continuum emission. Some of the lines display a degree of saturation in output with respect to current. Variation of the relative strength of these lines with respect to the continuum could be of significance in the spectral calibration process. This is discussed in detail.

9904-187, Session PS6

Application of Peterson's stray light model to complex optical instruments

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Gary L. Peterson (Breault Research Organization) presented a simple analytical model for in-field stray light evaluation. It assumes axial optical systems with rotational symmetry. Modelling the scatter distribution on each surface by Harvey-Shack parameters Peterson's approach describes the scattered ray cone at each optical surface in terms of marginal and chief rays and makes use of the optical invariant to trace them through the optical system. Assuming field points close to optical axis the model is able to give an analytical expression for the spatial distribution of the in-field stray light on the focal plane.

Since this approach allows a flexible and fast response within an engineering development cycle, we applied Peterson's idea to the more complex optical instruments of the Meteosat Third Generation (MTG) mission. For the Flexible Combined Imager (FCI) we evaluated the in-field stray light contribution of the front telescope assembly. It is a three-mirror-anastigmat (TMA) with an off-axis angle of 1.4°. For the infrared sounder (IRS) we performed an end-to-end analysis including the front telescope (TMA), interferometric and back telescope assembly and the cold optics. The analytical expressions are adapted to match the way the requirements are formulated. Results are compared with corresponding ASAP (stray light analysis software) simulations for both instruments. Applications for further optical and requirement engineering will be presented.

The MTG Program is being realised through the well-established cooperation between EUMETSAT and ESA. The industrial prime contractor for the space segment is Thales Alenia Space (France) with a core team consortium including OHB-Bremen (Germany) and OHB-Munich (Germany).

The authors acknowledge that this work is supported by an ESA funding through the MTG satellites development.

9904-189, Session PS6

Status of the ISS: image stabilisation system of the high-resolution telescope PHI on board of Solar Orbiter

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The polarimetric accuracy of the high-resolution telescope (HRT) PHI on board of Solar Orbiter requires very high precise pointing stability. To achieve the specifications, the jitter of the satellite pointing needs to be compensated by the image stabilisation system (ISS). The ISS will work as a correlation tracker with a piezo-driven Tip-Tilt mirror (M2 of the telescope) and a fast acquisition camera with more than 420 fps.

The presentation shows the performance of the ISS from simulations and laboratory tests in open and closed loop. Reports of the qualification of the already delivered Tip-Tilt drive and camera will be shown.

9904-190, Session PS6

Visible and near-IR detector technology for biosignature characterization

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The search for life on other worlds looms large in NASA's 30-year strategic plan. Already, two concepts exist for a flagship Large UV-Optical-IR (LUVOIR) Surveyor coronagraphic space telescope to search for spectroscopic biosignatures: ATLAST and HDST. Other teams are exploring smaller, more focused "probe class" missions to search for potentially habitable worlds. Taken collectively, these missions require technological advances in precision large-scale optics, ultra-stable structures, starlight suppression, mirror coatings, and detectors. Our focus is on visible and IR (VISIR) detectors for spectroscopic biosignature characterization.

NASA has a long and distinguished history building and operating VISIR space telescopes including IRAS, Hubble, Spitzer, JWST, and most recently WFIRST which is in the beginning stages of its mission lifecycle. These missions generally use semiconductor detectors (CCDs, EMCCDs, and IR arrays) for the VISIR. The lowest risk path forward is for LUVOIR to build on this heritage. However, even with a very large LUVOIR, biosignature characterization is still extremely low background astronomy. We discuss the "technology gaps" that exist between what today's semiconductor detectors deliver and the single photon detectors (SPD) that would be optimal for LUVOIR. In addition to high QE (and going beyond "photon counting"), an SPD has effectively no read noise and no dark count rate. With targeted investment, we believe that incremental improvements in the radiation hardness and sensitivity of today's semiconductor detectors are possible. We provide specific recommendations for how these improvement might be realized.

True SPDs (cryogenic detectors including STJ, TES arrays, and more recently MKID arrays), were first used for ground based astronomy about 20 years ago. These superconducting detectors have neither read noise nor dark current in the conventional sense. Moreover, they provide built-in energy resolution that eliminates the need for conventional spectrograph optics. These advantages are at least partly offset by the need for cooling to ~100 mK in the context of a space coronagraph that requires 10s of picometer wavefront error stability. Moreover, current LUVOIR concepts call for an essentially room temperature observatory. We discuss preliminary concepts for providing the required zero vibration cooling that leverage NASA's flight experience. We identify the "technology gaps" that exist between today's TES and MKID arrays and what is required for biosignature characterization. We recommend specific investments to mature both the cryogenic detectors themselves, and zero vibration cooling technology, so that both the detectors and cooling technology will be sufficiently mature in time for a LUVOIR by the mid to late 2020s.

Our recommended investment plan includes both low risk but incremental improvements in semiconductor detectors, and high risk but high payoff development of superconducting technology and zero vibration cooling. A balanced plan that offers both low risk but also the potential for breakthroughs offers the best chance of detecting potentially habitable worlds using space coronagraphs and biosignatures in the next 20 years.

9904-191, Session PS6

The shadow position sensors (SPS) formation flying metrology subsystem for the ESA-PROBA3 mission: present status and future developments

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The ESA PROBA3 Mission is the world's first precision formation flying (FF) mission. Two satellites, the OSC (Occulter Spacecraft) and the CSC (Coronagraph Spacecraft) will fly together in a fixed configuration, when observing at the Sun, as a large rigid structure in space to prove formation flying technologies and to observe the Sun corona at the same time.

The paired satellites will together form a 150 m long solar coronagraph whose aim is to study the faint corona closer to the solar limb than has ever before been achieved. Beside its scientific interest, the experiment will probe the instrument capability to measure the relative attitude and the positioning of the two spacecraft with respect to the Sun. To achieve the required performances (50 ?m transversal and 1 mm longitudinal accuracies are required) and to maintain the relative (i.e. between the two satellites) and absolute (i.e. with respect to the Sun) FF attitude, the Shadow Position Sensor (SPS) subsystem has been foreseen and designed along with some different spacecraft and payload devices dedicated to this function.

This subsystem is based on two independent sets (nominal and redundant) of four silicon photomultipliers able to sense the faint Sun coronal light with the required sensitivity and dynamic range as well. In order to determine the fine pointing of the two spacecraft to the Sun all the measurements coming from a set of devices will be combined thanks to a special algorithm based on a fitting procedure on the in-flight expected illumination profile. The latter shall be in-flight checked and re-calibrated with respect to the achieved profile thanks to the laboratory FF scaled model taking also into account the effects of the light diffracted by the edge of the external occulter hosted by the OSC.

The SPS subsystem error budget has been derived considering the error due to the algorithms fitting procedure as well as other sources of noise limiting the measurement accuracy, as the OSC tilt with respect to the CSC. Tilt, being one of the most important error terms, once properly assessed, could lead to a revised algorithm able to account also for the potential increasing of the number of degrees of freedom bonded to the tilt amplitude and requiring more SPS independent measurements. At the same time, the SPS flange is going to be designed taking into account several requirements concerning the measurements procedure, on-ground and in-flight calibrations and subsystem cleanliness as well.

This paper presents the recent advancements concerning the SPS subsystem design, its developed breadboard and Development Model (DM) as well as some preliminary tests performed on them, before going to realize the Structural and Thermal Model (STM), as required by the subsystem model philosophy.

9904-192, Session PS6

Preliminary evaluation of the diffraction behind the PROBA-3/ASPIICS optimized occulter

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PROBA-3 is a technological mission of the European Space Agency (ESA), devoted to the in-orbit demonstration of formation flying techniques and technologies. ASPIICS is an externally occulted coronagraph approved by ESA as payload in the framework of the PROBA-3 mission and is currently in its C/D phase. Classical space-borne externally-occulted coronagraphs are well suited to observe the extended corona but are limited in their performance by vignetting under 2 solar radii. The vignetting effect can be reduced by moving the external occulter farther from the rest of the telescope. Formation flying offers a solution to investigate the solar corona close the solar limb using a two-component space system: the external occulter on one spacecraft and the optical instrument on the other, separated by a large distance and kept in strict alignment. ASPIICS is characterized by an inter-satellite distance of ~144 m and an external occulter diameter of 1.42 m.

The stray light due to the diffraction by the external occulter edge is always the most critical offender to a coronagraph performance: the designer work is focused on reducing the stray light and carefully evaluating the residuals. In order to match this goal, external occulters are usually characterized by an optimized shape along the optical axis. The most effective optimization is based on a diffraction occultation principle that translates in a multiple disks system or in a solid shape along the optical axis, such as, for instance, a truncated cone. The baseline for the ASPIICS coronagraph in phase B has been a truncated cone, now changed to a toroid due to alignment stability and in-flight thermo-elastic deformation issues. Part of the stray light evaluation process is based on the diffraction calculation with the optimized occulter and with the whole solar disk as a source. The evaluation process is even more critical in the ASPIICS case, due to the impossibility of replicating the flight geometry in a laboratory clean environment. We used the field tracing software VirtualLabTM Fusion by Wyrowski Photonics to simulate the diffraction behind both a simple knife-edge and an optimized external occulter. We considered the whole solar disk as a source, and we applied a limb darkening model as well.

The sampling of the impinging electromagnetic wave is one of the key parameters to a successful diffraction evaluation. The definition of the correct sampling required a long preliminary activity and resulted in a great numerical effort that only a very powerful computer was able to bear.

This paper is dedicated to the description of the activity to define the correct set of parameters to be used in VirtualLabTM Fusion and to the results of the diffraction simulation. A comparison is shown among the performance of the simple knife-edge occulter, the toroid and the truncated cone in terms of stray light suppression.

9904-193, Session PS6

Trade-off between TMA and RC configurations for JANUS camera

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JANUS (Jovis Amorum Ac Natorum Undique Scrutator) is a high resolution visible camera designed for the ESA space mission JUICE (Jupiter Icy moons Explorer). The main scientific goal of JANUS, and the main drivers for the design, is to observe the surface of the Jupiter satellites Ganymede and Europa, and the atmosphere of Jupiter and other satellites during the orbit around the planet. In the case of Ganymede, in particular, it is foreseen a complete mapping of the surface with resolution higher than 400 m/px.

During the design phases, we have proposed two possible optical configurations: a Three Mirror Anastigmat (TMA) and a Ritchey-Chrétien (RC) both matching the performance requirements.

The first optical design adopted to meet the scientific requirements is an off-axis TMA with an entrance pupil diameter of 100 mm and two (out of three) mirrors with aspherical shape. The advantages of such a design are a diffraction limited optical quality and a good rejection of stray light due to the small number of optical surfaces and the absence of spiders. The high level of thermal stability required for JANUS, and the limits in terms of mass posed by the spacecraft, require the use of lightweight materials with low CTE like silicon carbide or carbon fiber.

The second optical design is a RC with two hyperbolic mirrors and a field corrector having an equivalent entrance pupil equal to the TMA solution. The advantages of such a solution are the lightness and compactness, the manufacturability and, in general, is more robust in terms of alignment process.

Here we describe the two optical solutions and compare their performance both in terms of achieved optical quality, sensitivity to misalignment and stray light performances.

9904-194, Session PS6

Alignment procedure for detector integration and characterization of the CaSSIS instrument onboard the TGO mission

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The Colour and Stereo Surface Imaging System (CaSSIS) is a stereo camera for the ExoMars Trace Gas Orbiter to be launched in 2016. CaSSIS is a high-resolution camera system capable of acquiring colour stereo images of surface features, possibly associated with trace gas sources and sinks, in order to better understand the range of processes that might be related to trace gas emission on Mars. The 4.5 m resolution on the surface of Mars will allow study of the evolution of possible liquid flows and to identify future landing sites.

The optical configuration of CaSSIS is based on a three-mirror anastigmatic off axis imager with a relay mirror. In order to attain telecentric features and to maintain compact the design, the relay mirror has power.

The University of Bern had the task of the detector integration as well as the characterization of the focal plane of CaSSIS. An OGSE (Optical Ground Support Equipment) characterization facility was set-up for this purpose. A pinhole, placed in the focus position of an off-axis paraboloidal mirror, was used to produce a collimated beam. This beam simulates a point like (star) object source placed at infinity which is conjugate with the CaSSIS focus plane. The pinhole could be illuminated either with monochromatic or white light.

In this work, the procedures to align the system and to link together the positions of each optical element will be presented. In particular a Reference System, that can be easily characterized, has been used to understand the mutual alignment of the optical components. The main steps to characterize the position of the object to that of the CaSSIS focal plane have been repeated to guide and to verify the operation performed during the alignment procedures.

In order to have a reliable Reference System, an optical cube has been placed on the optical bench (OBRS) and linked to gravity through its X component (GOBRS).

A calculation system has been designed in order to allow us to work on the optical setup and on the detector simultaneously, and to compute online the new position of the focus plane with respect to the detector.

Such a feedback system has been iterated to find the best position for the detector. All possible movements due to temperature and pressure changes between the lab and the on Mars operating condition have been taken into account. Final results will be shown and discussed.

9904-195, Session PS6

Design and development of a star sensor cum asteroid tracker

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We have developed a Star Sensor cum Asteroid Tracker to use in mini-satellites and Cubesats, whose main function is to estimate satellite's attitude / orientation. The sensor is essentially an imaging camera, which extracts information from the star patterns it records in the images. The field of view and limiting magnitude of the camera are decided to be 100 and 6.5m respectively from a sky simulation using the Hipparcos Bright Star Catalog to detect atleast 3 stars in a field pointed anywhere in the sky. A Tessar lens eliminating distortion and coma aberrations is designed and manufactured. The focal length and PSF of the optics is decided from the detector parameters like: pixel size, detector size etc. A radiation hardened detector Star 1000 is used in the system because of its suitability for applications in satellites. The detector is readout using a MIL grade Spartan-6 FPGA, the PCB for which is developed in-house. For online processing of the image data we implement a microcontroller called LEON SPARC v8. The VHDL source code for this core is available open source for educational and academic purposes from Aeroflex Gaisler. The main output of the star sensor is a quaternion which is estimated by processing data from the images acquired. In the process various algorithms are implemented viz. Centroiding algorithm, Geometric Voting algorithm, QUEST algorithm. An all sky simulation and various performance estimation tests of these algorithms is carried out to estimate the sky coverage where the algorithms work accurately, memory required

to implement the algorithms, time to calculate etc.

Having developed a real-time image processing platform on the FPGA board, its utility in other calculation intensive processes is being considered. Synthetic Tracking which essentially is stacking of images after shifting them slightly to compensate for object motion between images, is another such calculation intensive application where a large amount of RAM and processing power is required. We are currently working on implementing synthetic tracking on this hardware for a satellite based payload. This is achieved by making stacks of images for different velocities and then fitting a PSF to find objects in the stacked images which move with corresponding velocities. A suitable combination of such stacked images would help roughly estimate the orbital parameters of the asteroids and thus help in asteroid tracking.

9904-196, Session PS6

Achromatic interfero-coronagraph with variable rotational shear in laboratory experiments

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With the first definitive detection of an extrasolar planet in 1995 observational astronomy proved (by radial velocity method) the existence of planets around other stars in the galaxy. So far, indirect methods (i.e. non-imaging methods: radial velocity, transit photometry, astrometry, timing, microlensing) are the most successful in the exoplanet detection and characterization but they have substantial limitations and dependence on the model used to interpret observed data.

Despite all the efforts spent on the detection of exoplanets, both the direct imaging and spectral study of extrasolar planets and especially Earth-like planets remains very challenging research field. The reason is the critical combination of huge brightness contrast between the star and the planet (10^7 in the mid-IR and 10^10 in the visible and near-IR) and the small angular separation between sources (typically 0.1...0.5 arcsec and less).

To observe exoplanets directly and to perform further spectroscopic analysis we propose to use an achromatic interferometric coronagraph (AIC). AIC is in a particular place among the other designs because of the following notable features: starlight suppression is fully achromatic and inner working angle (IWA) of AIC 0.38?/D is the smallest of all coronagraphs. The latter one brings us to the significant drawbacks, high sensitivity to pointing errors and high sensitivity to angular star size which is known as star leakage effect.

Appreciable advance has been made since original AIC design had been published. The common path achromatic interferometric coronagraph (CP-AIC) was devised in 2005 as further development of AIC. CP-AIC uses the same starlight suppression principle as AIC with all its advantages and drawbacks mentioned in a mechanically stable and more robust way since it is a variation of a common path interferometer. In 2008 in order to decrease star leakage effect it was suggested to combine two common path interferometers in tandem to make a nuller which in theory provides an achromatic way to achieve 10^10 contrast with 0.01 ?/D effective angular star size at the expense of a throughput. In 2010 for the same purpose (to get over star leakage effect) the achromatic rotation-shearing coronagraph (ARC) was proposed.

An advantage of ARC over AIC is appreciable with telescope sizes more than 1 meter. The gain in contrast is up to 3 orders of magnitude higher relative to AIC with 2.4-meter telescope with achieved contrast about 10^9 that makes ARC appropriate for direct imaging of exo-Jupiter around nearest stars. There is also a significant gain in detection of exo-Earth around nearest stars since achieved contrast is about 10^5 with 2.4-meter telescope. In addition, ARC allows us to perform spectral analysis of planet light since it is an implementation of rotational shearing interferometer.

We detail achromatic interferometric coronagraph with variable rotational shear – common-path achromatic rotation-shearing coronagraph (CP-ARC), demonstrate laser light nulling and white light nulling with laboratory prototype and discuss possibilities of CP-ARC to carry out spectral analysis.

The reported study is funded by RFBR (grant No. 16-32-00440 ???_a).

9904-197, Session PS6

Thermal study of payload module for Millimetron Space Observatory

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Millimetron Space Observatory is a mission optimized for the submillimeter and far-infrared astronomy with a 10-m telescope which is cryogenically cooled down to 4,5K. Due to strict requirements on thermal performance, Millimetron mission will be launched into a halo orbit around the second Lagrange Point (L2) in the Sun-Earth system to obtain a stable thermal environment, which allows us to use effective radiative cooling in combination with a mechanical cooling system. Therefore, the telescope is equipped with large deployable thermal shields to block light and heat from the Sun, Earth, and Moon and cool the telescope passively to the temperature of 40 - 60K. The thermal shields are made from multiple layers of thin two-sided aluminium-plated films, supported by 12 deployable booms and a suit of pre-tensioned flexible cords from aramid fiber. Besides, there is the nearest to primary mirror cryogenic shield, which should be actively cooled to 20K. The thermal shield subsystem and the payload module basic structure with low thermal conductance separate the observatory into a warm sun-side part and a cold part.

This paper introduces details of the thermal design study for the payload module, in which the activity is focused on mitigating heat fluxes to the low temperature regions. First, the design of large deployable thermal shields will be discussed. Next, several development efforts to minimize parasitic heat loads to the cold and pre-cooling stages of mechanical coolers will be described. Finally, analytical results of the thermal design from recent studies will be presented. As the result of this study, the margins of the heat loads budget have been successfully satisfied, while the payload module structural design has been made to be more feasible and reliable.

9904-198, Session PS6

The front-end electronics of LSPE-SWIPE experiment

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The SWIPE detector of the Ballon Borne Mission LSPE (see e.g. the contribution of P. de Bernardis et al. in this conference) intends to measure the cosmic microwave background (CMB) intensity and polarization with very good precision. Detector is built around transition edge sensors and bolometers with a squid as a first stage very low noise preamplifier .

This contribution will concentrate on the design, description and first tests on the front-end electronics which processes the squid output (and controls it).

The squid output is first amplified by a very low noise preamplifier based on a discrete JFET input differential architecture followed by a low noise CMOS operational amplifier. The choice of the circuit topology and components value will be discussed together with preliminary results obtained so far at room temperature. Equivalent input noise density is 0.6 nV/√Hz and bandwidth extends up to at least 2 MHz. Both devices (JFET

and CMOS amplifier) have been tested at liquid nitrogen and the possibility to build a simple and cheap cryogenic preamplifier able to work even in liquid nitrogen will be discussed.

The second part of the contribution will discuss design and results of the control electronics, both the flux locked loop for the squid and the "slow control" chain to monitor and set up the system will be reviewed.

The circuit is composed by standard commercial components to simplify and quicken the design and production phase. Control electronics will operate in a reasonably warm environment and no special components are needed. Nevertheless much care is needed to monitor and correct the working conditions to improve stability and detect possible faults without introducing any noise.

The digital interface to the control computer will be discussed.

Finally future plans will be presented.

9904-199, Session PS6

The fabrication and DC performance qualification of the TES bolometers of LSPE

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The first upgraded release of the bolometers for the CMB Telescope SWIPE of the Balloon Borne Mission LSPE (see contribution of P. de Bernardis et al. in this conference) has been fabricated. This is based on a monolithic silicon excavated square chip where a large circular low stress silicon nitride membrane is suspended at the center. The chip rim act as mechanical, thermal and electrical interface to place and operate the bolometer inside the microwave optical cavity of SWIPE. The suspended spider web membrane covers an area as large as 50 mm2 and the TES sensor is placed in its center. In order to fulfil the performance requirements, the design of such upgraded detector has overcome a trade-off process among: (1) the large area need and (2)fabrication complexity and yield, (3) membrane stress relief and flatness, (4) internal thermal relaxation time among gold absorber and TES, (5) mechanical compatibility for the balloon flight operation. Similarly a second trade-off process among the necessary relative large production (about 300 chips) and the highly equalized operating characteristics and properly-tuned operating temperatures and dynamic range.

Concerning the first trade-off issues, we have successfully achieved good results by making a new design of the spiderweb geometry. It has been obtained numerically with mechanical and thermal models within the COMSOL software toolkit. The new design foresees the increase in number of the membrane suspending rods structure to reduce the strain that causes bending and consequently flatness loss. This is accompanied with a more robust membrane rim that distributes the tension and compression forces along the spiderweb perimeter. We have performed several simulations with COMSOL in order to set the design and fabrication processes to reach this requirements.

Further, the full set of thermal, mechanical and EM requirements have been included in a new design before the fabrication phase. Then we have produced two versions of bolometers with two TES type: TiAu bylayer to operate in the 350-400 mK range and MoAu bilayer for the alternative 500-550 mK range. After the production run, both types have been fully qualified in the corresponding operating temperatures in a dilution fridge, making IV-DC measurement and total noise spectra in a fully shielded isothermal cavity. This work has demonstrated that the new updated release has improved the flatness and shows a greater toughness in the fabrication process. Thermal conductance have been evaluated using usual models from bolometer IV-DC data laying in 3x10-11 W/K. Noise contributions are fully explained with Johnson and SQUID amplifier noise, with negligible excess noise. The recovery time constant has been tested with short diode laser pulses injected in the cavity via an optical fiber.

9904-200, Session PS6

PILOT optical alignment

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PILOT (Polarized Instrument for Long wavelength Observations of the Tenuous interstellar medium) is a balloon-borne astronomy experiment designed to study the polarization of dust emission in the diffuse interstellar medium in our Galaxy. The PILOT instrument allows observations at wavelengths 240 ?m (1.2THz) with an angular resolution about two arcminutes. The observations performed during the first flight in September 2015 at Timmins, Ontario Canada, have demonstrated the good performances of the instrument.

Pilot optics is composed an off axis Gregorian type telescope and a refractive re-imager system. All optical elements are in a cryostat cooled to 3K except the primary mirror, which is at ambient temperature (the room temperature during the end-to-end ground test or the temperature at ceiling altitude ~ 40 km in flight).

All optics system is aligned at room temperature and we have developed a dedicated procedure in order to keep the tight requirements on the focus position and ensure the instrument performances in the different environments.

We combined the optical, 3D dimensional measurement methods and thermoeslastic modeling to perform the optical alignment.

The talk describes the system analysis, the alignment procedure, and finally the performances obtained during the first flight.

9904-201, Session PS6

Near-infrared imaging spectrometer (NISS) onboard NEXTSat-1

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After the Science and Technology Satellite (STSAT) series, the next generation of small satellite program (NEXTSat) have been started from 2012, and it is the only space program for the space science in Korea. The NISS (Near-infrared Imaging Spectrometer for Star formation history) onboard the first small satellite of NEXTSat program is one of the scientific mission payloads and have being developed by KASI. To study the distant and local star formation, the NISS has a unique capability of both imaging and low spectral resolution spectroscopy in the wide near-infrared range. For those purposes, the main targets will be nearby galaxies, galaxy clusters, star-forming regions and low background regions.

Due to the limited mass and volume of NEXTSat-1, the NISS have adopted an off-axis optical design with a 15cm aperture. The NISS was optimized to achieve a wide field of view (FoV) of 2 deg. ? 2 deg. with a spatial resolution of 15 arcsec as well as a wide spectral coverage from 0.9 to 3.8?m. The imaging spectroscopy in the near-infrared range with no moving part was realized by using a special spectral filter combined of two linear variable filters. Most of mechanical structure including primary and secondary mirror was designed of the same material, aluminum to minimize thermal variations in the space. The opto-mechanical structure was designed to be safe enough to endure in both the launching and space environment. The telescope and infrared detector will be cooled down to 200K and 80K respectively through a passive and an active cooling with a small mechanical cooler. The electronics composed of a focal plane board and an electronics box have functions of operation of detector, electric interfaces with the spacecraft and a control of the NISS. The engineering model was delivered in 2015 and was tested in space environment. The flight model of NISS will be launched in 2017 and explore the large areal near-infrared sky up to 200 square degree in order to get both spatial and spectral information for astronomical objects.

9904-202, Session PS6

Testing and characterization of a prototype telescope for the enhanced laser interferometer space antenna (eLISA)

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The enhanced Laser Interferometer Space Antenna (eLISA) will enable study of gravitational waves in the 0.1 mHz to 1 Hz band inaccessible from ground-based observatories. A plethora of gravitational wave sources is expected in this frequency range, including supermassive black hole binaries and extreme mass ratio binary systems. The eLISA observatory consists of 3 spacecraft in a triangular formation separated by roughly 1 million kilometers a side, with each spacecraft housing free-floating inertial proof masses. Precision laser interferometry at 1064 nm is used to measure the proper displacement of these proof masses with high signal-to-noise as a passing gravitational wave stretches and shrinks spacetime between them. However, in order to perform laser interferometry over such vast baselines, telescopes are needed to provide more efficient exchange of laser beams between spacecraft. This function means that the telescope is in the interferometric beam path, and so its design is directly driven by the requirements of the gravitational wave observatory. Some of these specifications are very different from the usual imaging requirements of conventional telescopes.

As an example of differences from conventional telescopes, the overall noise budget of the gravitational wave observatory allocates less than 1 pm/√Hz displacement noise to the telescope in a band from 0.1 mHz to 1 Hz. This specification constrains the allowable optical path length change of the laser light passing through the telescope. A second, but related, constraint is due to the fact that the telescopes are used to both send and receive laser beams. While transmitting 1 W, the telescope also collects approximately 100 pW from the far spacecraft. Since both beams traverse the same optical elements, scattering has the effect of re-directing some of the outgoing light into the incoming mode. This cross-coupling, in tandem with unwanted displacement noise of the optical elements, can add phase noise to the interferometric measurement - effectively reducing the signal-to-noise with which we can study gravitational waves and their sources. The level of permissible scatter therefore depends on the dimensional stability of the telescope.

Here we describe our efforts to fabricate, test and characterize a prototype telescope for the eLISA mission. Much of our work has centered on the modeling and measurement of scattered light performance. This work also builds on a previous demonstration of a high dimensional stability metering structure using particular choices of materials and interfaces. We will discuss ongoing plans to merge these two separate demonstrations into a single telescope design demonstrating both stray light and dimensional stability requirements simultaneously.

9904-203, Session PS6

SINBAD electronic models of the interface and control system for the NOMAD spectrometer on board ESA ExoMars Trace Gas Orbiter mission

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NOMAD(Nadir and Occultation for Mars Discovery) is an instrument leaded by BIRA, IAA and OU. NOMAD is composed by three spectrometers, two infrared channels and one ultraviolet and visible channel. NOMAD will be part of the payload on board ESA ExoMars Trace Gas Orbiter Mission.

SINBAD is a NOMAD subsystem in charge of the communication and the management of the power and control between the spacecraft and the instrument channels. Two boards have been designed for these tasks, one board for the power distribution and housekeeping (POW board) and the other one (COM board) for the communication and control of the whole instrument with the spacecraft and the channels: telecommands and telemetry.

SINBAD System implements a microprocessor embedded in a FPGA. The telecommands are received via a 1MHz MIL-STD-1553B bus and the telemetry is sent through a 20MHz SpaceWire redundant bus. UVIS interface is a 1MHz RS-422 bus, while SO and LNO channels communicate through a 100MHz LVDS serial bus. The SINBAD system also controls the peripherals: sensors, actuators (flip mirror and pin-puller), heaters, ADC system.

First, a development board has been made to check the design and configurations, this board is customized with a LEON3FT microprocessor. It was designed in base to a set of stackable boards over a base one. The base board contains an ALDEC adapter with a programmable FPGA. It can be connected to memory and other boards through stackable connectors.

The next board developed (Prototype board) contains two interconnected FPGAs and has been used to check all the functionalities and also to test and develop the NOMAD EGSE.

The delivered models to the ESA were: NOMAD EIM, NOMAD STM, SINBAD PFM and SINBAD FS.

NOMAD EIM is an engineering model fully representative of the flight configuration with the spacecraft interface of the flight model. This model has resistive loads instead of scientific channels and the data and telemetry output is internally generated by software.

SINBAD EM is similar to the EIM, it has all the functionality and is devoted to SW development after the launch. This model has been tested with the last changes made to the system before the implementation into the flight models.

SINBAD PFM is the first model assembled with flight components for the functional testing. It was made in a clean room ISO 5. SINBAD PFM was tested with prototype version of UVIS, resistive loads and simulator for SO/LNO channels and a QM version of flip mirror with stepper motor and sensors. SINBAD PFM has been integrated with the channels and tested in NOMAD PFM. After the electrical and functional tests, this model has been tested for shock, vibration, vacuum and thermal environment.

SINBAD FS is the spare model and fully equal to SINBAD PFM. Both models have been validated to fly.

The NOMAD instrument will be launched from Baikonour in March 2016.

9904-204, Session PS6

Concept study for a compact planetary homodyne interferometer (PHI) for temporal global observation of methane on Mars in IR

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We propose to design, develop and demonstrate a new compact, high-performance, high spectral resolution Infrared (IR) spectrometer for Planetary Science of wide applicability to NASA sounding rockets, International Space Station (ISS) and Mars missions, Discovery and New Frontiers including those of planetary atmospheres and cometary science employing deep space missions, orbiting spacecraft, and on-surface landers or rovers.

Here, we will demonstrate capability by targeting Mars atmospheric methane measurement from space-based, Mars orbiter or surface platforms. Methane has been detected in the atmosphere of Mars using different approaches from in situ measurement by Curiosity, ground-based telescopic observations, and remote-sensing measurements from Mars-orbiting spacecraft MEX, MGS, and MRO. Although each approach has reported various results, these results are not necessarily contradictory, due to the possibility of spatial and temporal variability. Thus, more measurements and improved instrument measurement capabilities are required to gain clarity.

We present a concept study to build a new instrument to sequentially and over a long time measure methane abundance on Mars and find out its global seasonal variations, if any. The Planetary Homodyne Interferometer (PHI) offers integrated spectra over a wide field-of-view (FOV) in high spectral resolution (R~105) in a compact design using no (or a small < 1m) primary mirror. The architecture of PHI combines the high étendue of a Fourier Transform Spectrometer with higher optomechanical tolerance and simpler optomechanical design associated with grating spectrometers. PHI is best suited to studies of sources where temporally tracing specific spectral features sensitivity, and spectral resolution is of higher significance than spatial fidelity. We are targeting to measure the mid-infrared absorption of Mars atmospheric CH_4, H_2O, and CO_2 absorption lines by observing the full disk of Mars from Mars's orbit. By coupling the instrument to a small telescope, we will demonstrate measurement capability through laboratory measurements of trace methane in calibration gas mixtures and ground-based measurements of sodium around the Moon. The goal of developing PHI is to conduct planetary science instrument feasibility study, concept formation, proof of concept, and advanced component technology development of a miniature, high R, wide FOV spectrometer targeting spectral features of methane gas on Mars.

Various configurations of instruments similar to CHASE have been developed as proof-of-concept laboratory prototype, ground-based instrumentation, and sounding rocket experiments in the Optical, NUV and FUV wavelengths. These studies have demonstrated high R and high sensitivity UV spectrometers can be built in ultra-compact configurations similar to CHASE with no or small aperture telescope for a variety of space science applications.

9904-205, Session PS6

HST/WFC3: understanding and mitigating radiation damage effects in the CCD detectors

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At the heart of the Hubble Space Telescope Wide Field Camera 3 (HST/WFC3) UVIS channel is a 4096x4096 pixel e2v CCD array. While these detectors are performing extremely well after 7 years in low-earth orbit, the cumulative effects of radiation damage are becoming increasingly evident. The result is a continual increase of the hot pixel population and the progressive loss in charge transfer efficiency (CTE) over time. The decline in CTE has two effects: (1) it reduces the detected source flux as the defects trap charge during readout and (2) it systematically shifts source centroids as the trapped charge is later released. The flux losses can be significant, particularly for faint sources in low background images. In this report, we summarize the radiation damage effects seen in WFC3/UVIS and the evolution of the CTE losses as a function of time, source brightness, and image background level.

In addition, we discuss the available mitigation options, including target placement within the field of view, empirical stellar photometric corrections, post-flash mode and an empirical pixel-based CTE correction. The application of a post-flash has been remarkably effective in WFC3 at reducing CTE losses in low background images for a relatively small noise penalty. Currently, all WFC3 observers are encouraged to consider post-flash for images with low backgrounds. The pixel-based CTE correction software has been released as a standalone routine, to be applied to images after they are acquired. Analagous to the software currently in use in the HST Advanced Camera for Surveys (ACS) pipeline, the algorithm employs an observationally-defined model of how much charge is captured and released in order to reconstruct the image. The CTE correction software is planned for incorporation into the automated WFC3 calibration pipeline in early 2016.

9904-206, Session PS6

Performance of a cryogenic test facility for 4K interferometer delay line investigations

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Astronomical observations at far-infrared wavelengths provide a unique window to study both star formation in our own galaxy and highly redshifted emission from galaxies in the distant universe. The low energy of far-infrared photons necessitates the use of extremely sensitive detectors operating at sub-Kelvin temperatures. The optical noise equivalent power of state-of-the-art detectors is ~10^(-19) W/√Hz. To ensure that photon noise remains below this level, any spectroscopic instrument employing such detectors must be cooled to ~4 K. Ground-based, cryogenic facilities are required to evaluate the performance of materials, components and subsystems, prior to their implementation in space instrumentation. The University of Lethbridge Test Facility Cryostat (TFC) is such a facility, offering a high volume (70 L), low temperature (4 K) environment with a wide selection of metrology options. The first use of the TFC will be to test key components of the translation mechanism and metrology system of the high resolution spectrometer component of the SAFARI instrument being developed for the SPICA mission.

The TFC incorporates a complex wiring scheme for thermometry and metrology, as well as optical feedthroughs for laser metrology and infrared signal inputs. Cooling of the TFC is provided by dual Cryomech PT415 pulse tube cryocoolers with a total cooling power of 3 W at 4.2 K. In an effort to isolate pulse tube vibrations, a system of flexible copper braids is used to thermally couple the pulse tube and cold components. Multiple layers of radiative shielding, and cryogenic, zero-aperture irises are utilized to minimize radiative heat transfer. Parasitic heat conduction

from mechanical supports is minimized through the use of carbon-fibre-reinforced polymer (CFRP) struts with low thermal conductivity and high stiffness. Additionally, a liquid nitrogen precool system is included in order to decrease the system cooling time.

In order to test complete interferometer systems inside the cryostat, a composite, cryogenic blackbody source has been installed in the in the 4 K volume along with a Chase Research Cryogenics He-10 adsorption refrigerator to cool sensitive detectors to 0.3 K. Apertures have been designed into the TFC to allow for the use of multiple external instruments, including a Renishaw Differential Interferometer and a PLX Electronic Autocollimator. These instruments measure small displacements and rotations, respectively, providing accurate metrology for the characterization of material properties as well as metrology for cryogenic systems. The sensitive metrology provided by these instruments, and accurate internal thermometry, allow one to measure the thermal and mechanical properties of composite materials (e.g. CFRP) at low temperatures. A collaboration with Glyndwr University has been established to investigate the challenges associated with using CFRP in lightweight mirror structures at cryogenic temperatures. This paper discusses the design and performance specifications of the TFC, as well as the techniques used for measuring thermal conductivity, thermal expansion, and elastic modulus of composite materials.

9904-207, Session PS6

Current status of HAWAII-1RG characterization for NISS

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We present the current status of NISS electronics sensor characterization and optimization process. The Near-infrared Imaging Spectrometer for Star formation history (NISS) is a 15cm diameter off-axis reflector developed by Korea Astronomy and Space science Institute (KASI). It is one of two scientific mission payloads for the Next Generation Small Satellite 1 (NEXTSat-1) developed by Korea Advanced Institute of Science and Technology (KAIST). NISS will perform imaging spectroscopy for nearby galaxies, low-background regions and star-forming regions in NIR wavelength band ranging from 0.9~3.8um during the first two years. The NISS uses a HAWAII-1RG sensor as its detector, and two linear variable filters as dispersers with R=20. NISS electronics consists of three boards: DSP board is to generate housekeeping information and make command and status communication with the satellite system. A FPGA on the same board will perform 2 by 2 median pixel binning onboard the satellite to reduce the data amount, and serialize it for data communication. The amp board is for generation of sensor driving clock signal, and amplification of the output signal from the sensor. Lastly, Power board generates all electrical powers for NISS operation. All board designs have heritages either from MIRIS (Han et al., 2014) or CIBER-2 (Lee et al., 2015) HAWAII-1RG was successfully operated in the laboratory under 80K cryogenic condition with NISS EQM electronics boards. Several dark images were obtained along with reference channel images. Although the dark current turned out to be small, the standard deviation of pixel values in the resultant images were larger than expected. Revisions are being made to make HAWAII-1RG performance better. In addition, reference pixels around the imaging area of HAWAII-1RG will be utilized with scheme of Rauscher et al. (2011), to further reduce the noise. After the revisions, we will repeat the procedures again to confirm that the noise gets smaller down to the NISS specification. We will also measure our chip characteristics such as dark current level, pixel well depth, linearity range, and conversion gain, to determine the optimum sensor operation strategy for NISS science. The NEXTSat-1 is scheduled to be launched by a Falcon 9 rocket in the third quarter of 2017.

9904-208, Session PS6

Terahertz intensity interferometry for milli-arcsecond resolution

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High angular resolution imaging at far-infrared or terahertz frequencies are foreseen either using large single dish telescopes or interferometers. In this presentation we will focus on realization of a relatively long baseline intensity interferometer at terahertz frequencies which enables milli-arcsecond angular resolution.

Intensity interferometers were first demonstrated by Hanbury-Brown and Twiss.

However, low correlation efficiency and absence of phase information restricted their application to aperture synthesis imaging.

At terahertz frequencies, large number of bunched photons enables delay time measurements and high efficiency aperture synthesis imaging can be realized.

The principle of delay time measurement was recently demonstrated by an intensity interferometer experiment at microwave frequency; the delay time accuracy can be better than that corresponds to one wavelength using a large number of bunched photons.

The experiment showed that the intensity interferometer can be used for aperture synthesis imaging.

Application of intensity interferometry to space terahertz interferometer will be discussed in detail.

With the low background condition of cryogenic space telescopes, photon counting detector is advantageous for high dynamic range intensity measurements.

Intensity interferometry with terahertz photon counting detector can be named as the photon counting terahertz interferometry (PCTI).

Relatively low photon rate of 100 M photon/s from typical bright terahertz sources would realize delay time accuracy better than 0.1 ps within 100 s integration time.

Required NEP for photon counting is only less than 10(-17) W/rtHz when time resolution is 1 ns.

This sensitivity and time response can be realized by using low leakage current (1pA) superconducting tunnel junction detectors.

Combination of PCTI and double Fourier interferometer is proposed to achieve good uv coverage for aperture synthesis imaging in terahertz frequencies.

Shorter baseline is covered by the double Fourier interferometer and longer baseline by PCTI.

With baseline length of 20 km at 3 THz, angular resolution of 1 milli-arcsecond can be achieved.

In terahertz frequency region there are more than 100,000 cataloged point sources brighter than 1 Jy, which will be targets for the space terahertz interferometer.

PCTI can be applied to very long baseline intensity interferometer (VLBII).

Telescope systems on satellite platforms will be similar to space VLBI which use heterodyne receivers, but photon counting detectors will realize much higher sensitivity and wider bandwidth to imag thermal emission sources, such as stars and exo-planets.

9904-209, Session PS6

The latest results from DICE (Detector Interferometric Calibration Experiment)

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NEAT and Theia were proposed astrometric missions to ESA with the objectives of detecting Earth-like exoplanets in the habitable zone of nearby solar-type stars. Theia requires the capability to measure stellar centroids at an accuracy of 1e-5 pixel. Formerly called NEAT-demo, DICE aims to demonstrate that an interferometric calibration of the CCD can improve accuracy, up to the of previous specification. In this paper we present the latest results obtained after a series of major hardware upgrades. The analysis of the new set of data yielded an astrometric (centroid) accuracy of 6e-5 pixel.

9904-210, Session PS6

A cryogenic testbed for the characterisation of large detector arrays for astronomical and Earth-observing applications in the near to very-long-wavelength infrared

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We present the preliminary design of a cryogenic testbed for the complete characterisation of large arrays (> 1MP) of infrared detectors (including MCT), operating in the mid-infrared region (8–12 ?m), but also capable to operate in a region of the electromagnetic spectrum from the near-IR to the VLWIR. The testbed can be used to characterise the performance and scientific capabilities of focal planes for space missions such as Ariel, a candidate for the ESA M4 programme currently being studied by ESA, or other IR missions for astronomy and Earth Observing.

The testbed is capable of measuring the performance of the array, both dark and when optically loaded, from a base temperature of 4 K to in excess of 100 K, with high thermal stability (better than 1 mK over long time constants). It contains a filter wheel, driven by a cryogenic stepper motor. This allows the photometric band observed by the array to be switched between three narrow bands or a straight-through (unfiltered) mode. The image lag, also called the persistence effect, can be measured by moving the filter wheel to (or from) a blanked position to rapidly cut (or reinstate) the illumination on the array. The spectral response of the detector array is measured by moving the filter wheel to the unfiltered position and using a Fourier-transform spectrometer to measure the array response as a function of frequency. Finally, the modulation transfer function (MTF) and optical fill factor of the array can be measured by one of two techniques developed for this system. The first of these is an internal (to the cryostat) spot-projector system, which uses a thermal source and reflecting optics to project a focused, sub-pixel sized spot on to the array. This spot is then translated across the array using a three-axis cryogenic translation stage. As a second method for MTF characterisation, we have developed a novel system (at these wavelengths) to measure the average modulation transfer function of the entire array without the need for moving components. This technique uses the properties of so-called continually self-imaging gratings to generate an interference field that does not vary with propagation. To measure the MTF of single pixels using this technique, one need only move the input source of the collimator unit, which is external to the cryostat.

9904-211, Session PS6

Nanostructured optical devices for broadband applications including high contrast imaging and spectroscopy

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High contrast imaging of exoplanets requires masks to control or block the light from their parent stars from reaching the image plane where faint planet images may appear. A number of techniques have been explored to achieve better than 10-9 contrast between the star and the planet with partially obscured apertures such as WFIRST-AFTA. The shaped pupil coronagraph, a reflective mask with black silicon absorptive islands, is one of the architectures that has been produced and shown to meet milestone criteria. The same criteria could be met with nanostructured glass for transmissive geometry as the nanostructures reduce ghost reflections by modifying the optical admittance of the surfaces which would otherwise cause ghost images due to unwanted reflections. Similarly spectrometers involving prisms and/or gratings and slits require novel techniques to reduce scattered light and ghost reflections. Silts with nanostructures at the edges have enabled high performance spectrometers. Thirdly, silicon devices with increased transmission in the IR have become feasible with nanostructures; such devices while being extremely black in the visible show very high transmission in the IR, a property that could be exploited for many different applications. In this paper, we discuss the fundamental aspects of such nanostructures on surfaces that modify the surface properties in unique ways. We present illustrative examples of fabricated masks and other devices.

9904-212, Session PS6

Development of a near-infrared detector and a fiber-optic integral field unit for a space solar observatory SOLAR-C

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It's scientifically critical to make specto-polarimetric observations within a short time-scale to temporally resolve dynamic phenomena in observations of the solar chromosphere. For doing it in the next space-based solar mission, SOLAR-C, we are developing a high sensitivity and

fast readout near-infrared (NIR) detector and an integral field unit (IFU) for making a spectro-polarimetric observations of chromospheric lines, such as He I 1083 nm and Ca II 854 nm. The candidate NIR detector is 1.7 um cutoff HgCdTe H2RG sensor with SIDECAR readout ASIC. Because the detector is cooled only by a radiator in SOLAR-C, it's important to verify the performance in temperature condition around -100 deg C, which is hotter than the typical temperature used for a NIR detector. We built a system for testing the detector between -70 deg and -140 deg C. We verified linearity, read-out noise, and dark current etc. in both the slow and fast readout modes. We found the detector has to be cooled down lower than -100 deg C because of significant increase of number of hot pixels. The read-out noise was around 100 e in the fast readout mode, which is acceptable in the solar observation though we need further improvement and optimization. The IFU consists of fiber-optic bundles of rectangular cores, and we made test fabrication of the IFU and measured its properties of polarization maintenance. An issue was to find a way to fix the fiber bundles in a metal housing to make the fragile fiber-optics tolerant in mechanical environment for space application. Candidate materials for fixation were studied in terms of lower stresses to the fibers, lower viscosity to fill gaps between the fibers, and lower outgas. A silicone adhesive DC-SE9187L was selected and used to make a test piece of IFU. We made measurements of optical and polarization properties of the test IFU and confirmed its polarization maintenance property though polarization calibration and temperature control are necessary to meet polarization accuracy required.

9904-91, Session PS7

Low-noise flux estimate and data quality monitoring in Euclid NISP cosmological survey: how to fit a straight line in the precision cosmology era

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Euclid, a medium class cosmological survey from space, is designed to understand the origin of the universe's accelerating expansion. The survey will map the large-scale structure spanning over 70% of the age of the universe and provide constraints on the nature of dark energy and dark matter with unprecedented precision.

Precise spectroscopic and photometric redshifts, needed for the analysis of the galaxy clustering and 3 dimensional tomography of the universe, will be provided by the Near-Infrared Spectrometer and Photometer (NISP) equipped with 16 H2RG detectors.

A common technique used in the astronomical and cosmological applications is to read out near-infrared (NIR) arrays in the multiple accumulated sampling (MACC) - the accumulating signal is sampled up the ramp as a function of time. Multiple reads are averaged within groups to reduce the readout noise of the pixels and an equally weighted least square fit is applied to estimate the flux. This procedure completely neglects the fact that the data points are correlated and treats the samples as Gaussian distributed with constant variance.

As a pace mission, Euclid suffers from limitations of CPU and telemetry. The flux of the observed objects must be fitted in flight with an algorithm, which is not too demanding computationally. As the data points used to fit the fluence are not sent on ground, a reliable quality factor of the fit is required. A high precision and accuracy of the flux estimation and a rigorous control of the fit quality are fundamental to assure the strict goals of the mission. Optimal calculation of the flux in terms of signal to noise ratio should use all the information including correlated and uncorrelated errors in the covariance matrix. In that case flux must be computed using numerical methods, which is impossible in flight. For this purpose we propose a method of fitting the flux with Poisson distributed and correlated data, which is unbiased, has an analytic solution and provides a reliable quality factor of the fit. We compare our method to other common techniques of NIR signal estimation and illustrate the anomaly detection, such as nonlinearity or cosmic ray hits, using the quality factor on the flight-like engineering detectors.

Although our discussion is focused on Euclid NISP instrument, we anticipate that much of what is discussed will be of interest to any cosmological mission using similar near-infrared sensors.

9904-165, Session PS7

Small-grid dithers for the JWST coronagraphs

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The James Webb Space Telescope (JWST) will be equipped with a suite of coronagraphs allowing observers to detect faint sources near or around bright stars and galaxies. Coronagraphic observations typically rely on subtracting a reference star point spread function (PSF) from the science target in order to remove the bright stellar speckles and improve the detectability of faint surrounding objects such as planets and disks. The accuracy of the target acquisition operation on the reference star is very important in order to match the science target and achieve optimal contrast. This is particularly true with phase masks on JWST, which are very sensitive to pointing accuracy. Here, we discuss the results of simulations of a new JWST mode that utilizes many sub-pixel dithered reference images, called Small-Grid Dithers, to optimize coronagraphic PSF subtraction. These sub-pixel dithers are executed with the Fine Steering Mirror under closed-loop fine guidance and are accurate to 2-3

milliarcseconds (mas; 1-sigma/axis). Sub-pixel dithers are limited to ~60 mas, but provide ample speckle diversity to reconstruct an optimized synthetic reference PSF with the use of a variety of algorithms (e.g; LOCI or KLIP). Using realistic noise sources and jitter in simulated images, we discuss and evaluate the performance gains of Small-Grid Dithers compared to the standard target acquisition scenario for both the NIRCam and MIRI coronagraphs. In particular, we find that Small-Grid Dithers can improve contrast by a factor ranging from 2 to more than 10 for the NIRCam and MIRI coronagraphs respectively.

9904-214, Session PS7

The mehod of searching F/G/K type hyper-velocity star candidates from data release one of LAMOST survey

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Hyper-velocity stars (HVSs) are believed to be ejected out from the Galactic center through dynamical interactions between stars and the central massive black hole(s), and they are the decisive evidence of Galactic center super-massive black hole. Therefore, searching for HVSs (or candidates) is a extremely important work, especially how to discover them from massive spectra, which are obtained by the large scale spectroscopic survey, with carefullydesigned criteria. In this work, we develop five steps to select HVS candidates from the LAMOST massive spectra based on the features of LAMOST data products, and we report 19 low mass F/G/K type hyper-velocity star candidates from over one million stellar spectra of the first data release of the LAMOST general survey.

9904-215, Session PS7

Data processing and algorithm development for the WFIRST-AFTA coronagraph

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Direct detection and characterization of mature giant or sub-Neptune exoplanets in the visible will require space-based instruments optimized for high-contrast imaging with contrasts of 10ˆ-9. In this context, the Wide-Field Infrared Survey Telescope (WFIRST) coronagraph will reach raw contrasts of about 10ˆ-8 or better using state-of-the-art starlight suppression and wavefront control techniques. A ten-fold contrast improvement is therefore required using post-processing techniques in order to detect 10ˆ-9 planets from speckles. Post-processing techniques that are successful on both ground-based and space-based instruments need to be validated at such high contrast levels. In particular, the temporal and chromatic evolutions of residual speckles raise new challenges for these methods. We investigate PSF subtraction techniques for different observation strategies on WFIRST-like images in the presence of deformable mirrors and a coronagraph. In this communication, we present results applied to both simulated datasets and experimental data from the High Contrast Imaging Testbed at JPL, in particular for the WFIRST coronagraph integral field spectrograph (IFS). We demonstrate that PCA-based PSF subtraction using reference images obtained shortly before a science sequence can improve contrast by a factors of 5-30x and 2-4x respectively for simulated and experimental data.

9904-216, Session PS7

Sensitivity analysis of a direct broadband sensing algorithm

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Most coronagraphic instruments use a slow adaptive optics control loop for nulling midspatial frequencies to create a region of high contrast in the focal plane and enable high-contrast imaging of exoplanets. To enable accurate estimation of the wavefront, typically narrowband filters are used in conjunction with deformable mirror probing the science camera focal plane. Recently, we have presented a concept to enable estimation in direct broadband light by using probes that introduce spatially-localized chromatic diversity. Here, we determine the sensitivity of the algorithm in terms of the estimation accuracy of the chromatic spectral component as a function of the input broadband bandwidth. Additionally, we investigate the chromatic estimation error induced by the proximity of probes in the focal plane in order to enable maximal focal plane coverage. Finally, we compare the performance of the direct broadband estimation scheme with a typical narrowband estimation scheme.

9904-217, Session PS7

Centroiding procedure for the PROBA-3 OPSE metrology sub-system's PSF

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Metrology in distributed systems for space applications is one of the most important technology research fields that in recent years have raised increasing interest. Many applications of astronomical observation techniques, as coronography and interferometry get great benefit when moved in space and the employment of distributed systems represents a milestone to step-over in astronomical research. In this work, we present the Optical Position Sensors Emitter – OPSE metrology sub-system on-board of the PROBA3. PROBA3 is an ESA technology mission that will test in-orbit many metrology techniques for the maintenance of a Formation Flying with two satellites, in this case an occulter and a main satellite housing a coronagraph named ASPIICS, kept at an average inter-distance of 144m. The scientific task is the observation of the Sun's Corona at high spatial and temporal resolution (target is the get close to the Sun limb down to 1.08R?). The OPSE will monitor the relative position of the two satellites and consists of three emitters positioned on the rear surface of the occulter that will be observed by the coronagraph itself. A Centre of Gravity algorithm is used to monitor the emitter's PSF at the focal plane of the Coronagraph retrieving the Occulter position with respect to the main spacecraft with a target measurement accuracy of 300microns for

lateral movements and of 20cm for longitudinal movements. A preliminary assessment of the centroiding performances is given.

9904-218, Session PS7

Probability density function approaches to completeness

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Completeness is a useful metric for exoplanet direct imaging mission analysis and design. It is the probability of a planet falling outside the telescope's obscuration and being bright enough to be detected. Assuming probability density functions for orbital elements (semimajor axis, eccentricity, and orbital orientation) and planetary properties (geometric albedo, radius, and phase function) of planets of interest, a joint probability density function of planet-star separation and difference in brightness between star and planet is found. Completeness is straightforward for a single observation but can also account for multiple observations of the same star at different epochs. Benefits of completeness studies of exoplanet observations include realistic expectations of mission outcomes based on objective terms for search power and a scientific metric to inform and optimize designs.

Single-visit completeness is determined by the assumption that an exoplanet is observable if its angular separation from its star is greater than the observatory's inner working angle (IWA) and less than the observatory's outer working angle (OWA) while also being illuminated such that the difference in brightness between the star and planet is below a limiting value where confusion between the planet signal and noise occur. Dynamic completeness is the completeness of the nth observation of a target star. It is dependent on the elapsed time after the first observation and subsequent observations. Each successive observation reduces the maximum possible value of dynamic completeness. It rebounds from zero just after observation to a time dependent value as planet positions propagate.

Most completeness calculations have relied on Monte Carlo trials because of the complexity of the assumed distributions. A large, equal number of samples are generated from each of the distributions and star-planet separation and difference in brightness are calculated for each set. A two-dimensional histogram of these values generates the completeness joint probability density function. Integrating with respect to separation and difference in brightness over this joint probability density function yields the completeness. The completeness distribution must be sampled fully to find any one point of the joint probability distribution accurately. Because of the number of parameters involved and the wide range of values each of these parameters may take, full sampling requires a large number of Monte Carlo trials. Increasing numbers of Monte Carlo trials increases the computational time of accurately determining completeness.

For exoplanet mission simulators performing such calculations on the fly, it is desirable to produce such calculations quickly. Faster methods of accurately calculating completeness are desirable.

We present probability density function approaches to compute single-visit and dynamic completeness which are computationally faster and avoid the undersampling problem inherent in Monte Carlo approaches. The single-visit completeness joint probability density function is derived from the probability density functions necessary for determining planet-star separation and difference in brightness. Dynamic completeness is computed by incorporating the elapsed time between observations into the single-visit completeness joint probability distribution function. These approaches are computationally faster than performing large Monte Carlo simulations at each successive simulated observation.

9904-219, Session PS7

Performance analysis of the GR712RC dual-core LEON3FT SPARC V8 processor in an asymmetric multi-processing environment

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In recent years, data rates and volumes produced by scientific space missions have increased exponentially with consequent new highly demanding requirements on onboard data processing and storage. The high costs in terms of memory and bandwidth increased the need of onboard analysis and compression of the collected data before they are sent to ground.

One possible solution is to have HW systems, e.g. ASICs, dedicated to these onboard activities, but the effort made in the past for producing powerful general purpose radiation tolerant European processors like the Aeroflex Gaisler UT699 LEON3FT SPARC V8, provided an indication of the possibility to implement an alternative and more flexible pure software solution.

In particular, past comparative studies showed the potentialities of the single core LEON3FT, which resulted to be one of the eligible onboard processors for implementing both instrument control and data acquisition and pre-processing functionalities in some of the future medium size missions proposed within the ESA Cosmic Vision program, e.g. Plato, ECho, Ariel.

However, the processor performances have shown to be less appealing when dealing with the very high demanding compression needs of survey missions like Euclid, where huge focal plane arrays (>600Mpix) coupled with stringent compression time requirements made the single-core LEON3FT unusable, forcing either the adoption of dedicated compression HW in the design, or the switching to the use of a more powerful non European processor, e.g. PowerPC based processors like the RAD750 of BAE Systems Information and Electronic Systems Integration Inc.

With the aim of finding a solution to these kind of needs based on the use of a European processor, the possibility to use a multi-core approach has been investigated. More specifically, we decided to start our investigation by carrying out a series of performance tests using a prototype board mounting the Cobham Gaisler GR712RC Dual-Core LEON3FT processor.

The application benchmark is based on the use of the same lossless compression algorithms used in the past for characterizing the performances of the LEON3FT single core. This choice allows a direct comparison with both the previously presented Leon3 results and the measured performances on architectures based on the use of PowerPC. The algorithm is based on a University of New Mexico open source implementation of the CCSDS 121.0-B-1 lossless compressor.

The hardware environment of the test consists of a homogeneous multi-core system architecture with a single bus and shared memory. The software environment is based on the use of RTEMS as operating systems, used in Asymmetric Multi Programming mode. The idea is not to develop a parallel implementation of the algorithm, but to split the overall compression activity into autonomous sub-tasks, acting on independent data sets covering separate portions of the overall focal plane array. The tasks run asynchronously on the individual cores, configured to have separate memory addressable areas and hardware resources. The task communication is implemented by means of standard IPC mechanisms.

To measure the performance we propose here a parametric approach which tests the effect of a variable workload to optimize the shared resources.

9904-220, Session PS7

On-board data processing for the near infrared spectrograph and photometer instrument (NISP) of the Euclid mission

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The Near Infrared Spectrograph and Photometer (NISP) is one of the two instruments on board the EUCLID mission now under implementation phase. The focal plane detector mosaic consists of 16, 2048x2048 pixels^2 HAWAII-II HgCdTe detectors, now in advanced delivery phase, from Teledyne Imaging Scientific (TIS), and will provide NIR imaging in three bands (Y, J, H) plus slitless spectroscopy in the range 1.1-2.0 micron.

All the observational modes will be supported by different parametrization of the classic Multi-Accumulation IR detector readout mode.

Due to the large number of deployed detectors and to the limited satellite telemetry available to ground, a consistent part of the data processing, conventionally performed off-line, must be accomplished on board, in parallel with the flow of data acquisitions.

This has led to the development of a specific on-board HW/SW data processing pipeline, and to the design of performing control electronics, suited to cope with the time and data flow constraints of the NISP acquisition sequences.

In this paper we present the architecture of the NISP on-board processing system, which interfaces directly to the SIDECAR ASICs managing the detector focal plane, as well as the implementation of the computational aspects of the data-processing i.e. frame co-adding, final frame computation and data compression before transmission to ground.

9904-221, Session PS7

The Precision Projector Laboratory: a facility for emulating high precision astronomical observations

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As astronomical observations from space benefit from improved sensitivity and calibration accuracy, poorly understood image sensor behavior threatens to limit the science reach of missions that demand increasingly strict control of systematic errors. Conventional detector characterization provides a bottom-up path to understanding the underlying detector physics and aids the development of ever more faithful numerical simulations; however, this approach is vulnerable to preconceptions and simplifications. An alternative top-down approach is laboratory emulation, which enables observation, calibration, and analysis scenarios to be tested without relying on a complete understanding of the underlying detector physics. Emulation complements conventional characterization and simulation efforts by testing their validity, and it reduces mission risk by revealing anomalous detector behavior only apparent in science-like images.

This paper describes the Precision Projector Laboratory (PPL), an emulation facility run by Jet Propulsion Laboratory and Caltech Optical Observatories. The primary experimental apparatus is an Offner Relay that projects "scenes" (stars, galaxies, spectra, etc.) with low optical aberration over the full area of a typical optical or near infrared image sensor. The scenes are etched onto high-resolution chrome-on-glass masks and reimaged at unity magnification. Focal ratios of f/8 and slower may be selected, spanning those of most proposed space missions. High Strehl point-spread functions are achieved over a wide field of view and wavelength range to deliver highly predictable image patterns with sub-pixel resolution, stable intensity, and fine motion control.

PPL supports various instruments requiring validation or rapid characterization using science-like data, in particular, the emulation of weak gravitational lensing measurements by the Wide Field Infrared Survey Telescope and high precision spectrophotometry of transiting exoplanets by James Webb Space Telescope.

9904-222, Session PS7

Design-oriented analytic model of phase and frequency modulated optical links

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High-dynamic range optical links, in which the microwave signal is modulated on an optical carrier, are emerging as an enabling sub-system in different applications such as antenna remoting, beamforming, and optical pre-processor for Photonic Analog to Digital Converters. Amplitude modulation was firstly investigated, and either direct modulation of the laser source or external modulation by means of Mach-Zehnder interferometers in consolidated LiNbO3 technology have been considered, according to system requirements in terms of cost, size, and performance.

In recent years, also phase and frequency modulation of the optical carrier are emerging as alternatives to amplitude modulated links, due to their modulation efficiency and spectral purity. A quadrature biased Mach-Zehnder interferometer was first considered as frequency discriminator at the receiver side. However, its linearity is not sufficient to achieve requirements in terms of Spurious-free dynamic range in most of the applications. Digital filter design techniques have been investigated for the design of optical filters working as frequency discriminator: these components show superior performance in terms of linearity, on the other one designed optical filters can be implemented as a photonic ASIC so reducing cost and size.

A key point for the design of both directly and externally-modulated links is the availability of models for the optical and electrical components, in order to estimate achievable performance during the design phase. In this paper, an analytic design-oriented model of phase and frequency modulated microwave optical links has been developed, that allows link design and performance simulation. A key part of the model is the non-linear and noise model of a Mach-Zehnder interferometer, which allows external phase modulation of the RF input signal. It has to be noted that the frequency roll-off of the optical response is considered. Also the model of the receiver has been developed, consisting of the frequency-dependent transfer function of the discriminator, evaluated in terms of coefficient of the designed digital filter. If needed such coefficients can be expressed as a function of coupling ratios and phase shifts of the related FIR lattice filter that is suitable for implementation as a photonic ASIC. Finally, also the frequency- dependent response of the receiver photodiode has been considered.

In order to demonstrate the feasibility and usefulness of the developed model, it has been used to design and compare links with different discriminators in terms of linearity, gain and dynamic range. Effects of the residual intensity modulation on receiver linearity have been taken into account in the model. All designed discriminators are suitable for implementation as planar lightwave circuits.

9904-223, Session PS7

The quick-look software of the Euclid NISP instrument workstation

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The Near Infrared Spectro-Photometer (NISP) on board the Euclid ESA mission will be developed and tested at various levels of integration using various test equipment which shall be designed and procured through a collaborative and coordinated effort. The Electrical Ground Support Equipment (EGSE) shall be required to support the assembly, integration, verification and testing (AIV/AIT) and calibration activities at instrument level before delivery to ESA, and at satellite level, when the NISP instrument is mounted on the spacecraft. An important part of the EGSE is the Instrument Workstation (IWS). The main aim of the this workstation is to archive the instrument data in raw and in FITS format and to perform in near real-time or in retrieval mode the quick look analysis and some offline analysis required to monitor and verify the instrument functionalities and performances throughout the various phases of the NISP lifetime. Herein we describe the data flow and processing which will need to be performed by the IWS at the various stages of integration. In particular we explain in detail the requirements on the quick-look software which will allow the monitoring of the many stages in the instrument assembly, integration and verification. This software, written in the IDL language, allows access in near real time and in retrieval mode all the instrument data and provides the 1-D, 2-D and 3-D display and analysis tools required to verify the instrument functionalities and performance using both the HK and the Science data.

9904-224, Session PS7

Gain determination of non-linear IR detectors with the differential photon transfer curve (dPTC) method

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Conversion gain is a basic detector property which relates the raw counts in a pixel in data numbers (DN) to the number of electrons detected. The standard method for determining the gain is called the Photon Transfer Curve (PTC) method and involves the measurement the change in variance as a function of signal level. For non-linear IR detectors, this method depends strongly on the non-linearity correction and is therefore susceptible to systematic biases due to calibration inaccuracies. We have developed a new, robust, and fast method, the Differential Photon Transfer Curve (dPTC) method, which is independent of non-linearity corrections, but still delivers gain values similar in accuracy and precision.

9904-225, Session PS7

High-fidelity multi-scale local processing for visually optimized FIR/sub-mm Hershel images

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In the context of the Hi-Gal full-plane multi-band mapping of the galactic plane, acquired with the Herschel far-infrared/sub-mm satellite, we have developed a powerful pipeline which produces high definition and high quality color maps, optimized for visual perception of image features. The tool projects the tiles of three selected band maps onto a 3-channel stripe, spanning 360° of galactic longitude by 2.8° galactic latitude, at the resolution of 3.2"/pixel, which is then processed by a custom multi-scale local stretching algorithm, endowed of local color balance and contrast tuning. A further edge-preserving contrast enhancement algorithm is finally applied, in order to perform artifact-free details sharpening. With this tool we have thus produced a giga-pixel color image of the whole galactic plane which join the 70?m, 160?m and 250?m maps and can be navigated in the ViaLactea web site.

9904-226, Session PS7

The boot software of the control unit of the near infrared spectrograph of the Euclid space mission: technical specification

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The Near Infrared Spectrograph and Photometer (NISP) is one of the instruments on board the ESA EUCLID mission. The Universidad Politécnica de Cartagena and Instituto de Astrofísica de Canarias are responsible of the Instrument Control Unit of the NISP (NI-ICU) in the Euclid Consortium. The NI-ICU main functions are:

- communication with the S/C and the Data Processing Unit via 1553 IFs
- control of the Filter and Grism Wheels
- control of the Calibration Unit
- thermal control of the instrument

The Boot Software (BSW) in a space program is a non-patchable, autonomous software that runs on the CPU and performs a small number of tasks: initialization, self tests of vital HW, memory management (dump, load, check), loading a patchable Application Software (ASW), and giving control to the loaded ASW.

The main features of a BSW design are the following:

• It must be flawless. The BSW is non-patchable, therefore a BSW bug cannot be fixed. A systematic failure can put in jeopardy a complete space program, losing many years of dedicated work and hundreds of millions of euros.

However, there is no such a thing as a flawless SW by design. A complete development process is put in place in order to minimize the probability of flying with buggy SW. The process includes several testing campaigns (with different means and objectives), thorough analysis and continuous reviews.

• It must be robust. Robustness is the ability to cope with errors during

execution. During the 6.5-years mission in space, many events will occur. Some of them can be foreseen, some other will be unexpected. The main external environment events are SEUs (Single Event Upsets, when a charged particle, e.g. a proton, collides with the Spacecraft and changes the value of a bit in memory), and HW degradation (due to continuous radiation). The Spacecraft interfaces could also be degraded, but in any case, no single failure shall lead to a system loss. Before critical decisions are taken, a design mechanism is put in place in order to avoid a single error to trigger a fatal scenario.

Software design techniques deal with expected and unexpected events in order to reach the robustness goal. Features like defensive programming, last-survivor policy, and data reporting approach are key to a successful BSW.

This paper presents the NI-ICU BSW Technical Specification definition and the analysis that optimizes the fulfillment of the design objectives.

9904-227, Session PS7

Simulating observations with the JWST NIRSpec integral field unit and a comparison with the E-ELT/HARMONI

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With the James Webb Space Telescope (JWST) due to launch in 2018 it is becoming ever more critical to prepare for observations by quantitatively analysing its science capabilities, and thus maximising operating efficiency. To this end we have extended the HARMONI simulation package HSIM of Zieleniewski et al. to develop a Python software package capable of simulating observations using the NIRSpec integral field unit (IFU) on the JWST. The software handles input datacubes and creates mock observed datacubes, folding in background, throughput and noise models for the telescope and instrument. It also utilises the WebbPSF package to incorporate detailed point spread functions into simulations. The software allows astronomers to quantitatively assess the feasibility of observations in much greater detail than offered by simple exposure time calculators. We perform an extensive set of simulations of high redshift emission-line galaxies, covering a range of morphologies, redshifts and star formation rates and derive simple limits for the detection and kinematic analysis of these objects. We further compare the performance of NIRSpec to the ground-based HARMONI instrument on the European ELT, and demonstrate the synergies between these two future IFUs.

9904-228, Session PS7

A rigorous approach to the production of reference files for JWST/NIRCam

Massimo Robberto, Bryan Hilbert, Space Telescope Science Institute (United States); Jarron M. Leisenring, Karl Misselt, The Univ. of Arizona (United States); Armin Rest, Space Telescope Science Institute (United States); Marcia Rieke, The Univ. of Arizona (United States)

One of the main outcomes of the final cryo-vacuum tests of a space instrument like JWST/NIRCam is the production of reference files suitable for science calibration in the early phases of the mission. Reference files are required by nearly every step of the pipeline, from raw data to final mosaic images astrometrically and photometrically corrected. Their construction, largely based on extensive sets of darks and illuminated images, must not only take into account the flow of the pipeline, but also prevent the injection of spurious systematics and correlations, while providing a robust estimate of the added uncertainty added at each step, needed for correct noise propagation. In this contribution we describe the approach followed for JWST/NIRCam using the data collected in the final cycle of cryo-vacuum tests (CV3) at NASA Goddard.

9904-229, Session PS7

Is there a best method for removing correlated noise from Spitzer exoplanet photometry?

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At infrared wavelengths secondary eclipses and phase curves are powerful tools for studying a planet's atmosphere. Extracting information about atmospheres, however, is extremely challenging due to the small differential signals, which are often at the level of 100 parts per million (ppm) or smaller, and require the removal of significant instrumental systematics. For the IRAC 3.6 and 4.5 ?m InSb detectors that remain active on post-cryogenic Spitzer, the interplay of residual telescope pointing fluctuations with intrapixel gain variations in the moderately under sampled camera is the largest source of time-correlated noise. Over the past decade, a suite of techniques for removing this noise from IRAC data has been developed independently by various investigators. In summer 2015, the Spitzer Science Center hosted a Data Challenge in which 7 exoplanet experts, each using a different noise-removal method, were invited to analyze 10 eclipse measurements of the hot Jupiter XO-3 b, as well as a complementary set of 10 simulated measurements. In this contribution we review the results of the Challenge. We describe statistical tools to assess the repeatability, reliability, and validity of data reduction techniques, and to compare and (perhaps) choose between techniques.

9904-230, Session PS7

Spitzer IRAC pipeline: final modifications and lessons learned over a mission

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In more than ten years of operations, the Spitzer Space Telescope has conducted a wide range of investigations from observing nearby asteroids to probing atmospheric properties of exoplanets to measuring masses of the most distance galaxies. Observations using the Infrared Array Camera (IRAC) at 3.6 and 4.5um are likely to continue through 2018 when the James Webb Space Telescope will succeed Spitzer. In anticipation of the eventual end of the mission, the basic calibrated data reduction pipeline designed to produce flux-calibrated images has been finalized and used to reprocess all the data taken during the Spitzer warm mission. We discuss final modifications made to the pipeline.

9904-231, Session PS7

The instrument workstation for EGSE of the near infrared spectro-photometer instrument (NISP) of the Euclid mission

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The NISP instrument on board the Euclid ESA mission will be developed and tested at different levels of integration using various test equipment which shall be designed and procured through a collaborative and coordinated effort. The NISP Instrument Workstation (NI-IWS) will be part of the EGSE configuration that will support the NISP AIV/AIT activities from the NISP Warm Electronics level up to the launch of Euclid. One workstation is required for the NISP EQM/AVM, and a second for the NISP FM. Each workstation will follow the respective NISP model after delivery to ESA for Payload and Satellite AIV/AIT and launch. At these levels the NI-IWS shall be configured as part of the Payload EGSE, the System EGSE, and the Launch EGSE, respectively. After launch, the NI-IWS will be also re-used in the Euclid Ground Segment in order to support the Commissioning and Performance Verification (CPV) phase, and for troubleshooting purposes during the operational phase.

The NI-IWS is mainly aimed at the local storage in a suitable format of the NISP instrument data and metadata, at local retrieval, processing and display of the stored data for on-line instrument assessment, and at the remote retrieval of the stored data for off-line analysis on other computers.

We describe the design of the IWS software that will create a suitable interface to the external systems in each of the various configurations envisaged at the different levels, and provide the capabilities required to monitor and verify the instrument functionalities and performances throughout all phases of the NISP lifetime.

9904-232, Session PS7

Cross validation of a yield tool based on the EXOSIMS framework

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The new large mission study concepts for the direct imaging of exo-earths present an exciting opportunity for exoplanet discovery and characterization. While these telescope concepts would also be capable of conducting a broad range of astrophysical investigations, the most difficult technology challenges are driven by the requirements for imaging exo-earths. The exoplanet science yield for these mission concepts will drive design trades and mission concept comparisons.

To assist in these trade studies, the Exoplanet Exploration Program Office (ExEP) is developing a yield estimation tool that emphasizes transparency and consistent comparison of various design concepts. The tool will provide a parametric estimate of science yield of various mission concepts using contrast curves from physics-based model codes and Monte Carlo simulations of design reference missions using realistic constraints, such as solar avoidance angles, the observatory orbit, propulsion limitations of star shades, the accessibility of candidate targets, local and background zodiacal light levels, and background confusion by stars and galaxies. The Python tool utilizes Dmitry Savransky's EXOSIMS (Exoplanet Open-Source Imaging Mission Simulator) design reference mission simulator that is being developed under the WFIRST Preparatory Science program. ExEP is extending and validating the tool for future mission concepts under consideration for the upcoming 2020 decadal review.

The validation of the tool utilizes two approaches. The first approach uses a synthetic star list and Brown completeness to calculate point comparison and evaluate known parametric trends. The comparison is used for both unit testing and end-to-end validation. The second approach is an end-to-end cross-validation against an independently generated consistent comparison of Exo-S, Exo-C, WFIRST/AFTA, and WFIRST/AFTA with Starshade (Traub, in preparation). We present the validation results for both validation approaches.

9904-254, Session PS7

The control unit of the near infrared spectrograph of the Euclid space mission: detailed design

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The Near Infrared Spectrograph and Photometer (NISP) is one of the instruments on board the ESA EUCLID mission. The Universidad Politécnica de Cartagena and Instituto de Astrofísica de Canarias are responsible of the Instrument Control Unit of the NISP (NI-ICU) in the Euclid Consortium. The NI-ICU main functions are:

- communication with the S/C and the Data Processing Unit via 1553 IFs
- control of the Filter and Grism Wheels
- control of the Calibration Unit
- thermal control of the instrument

The NI-ICU follows a cold-redundancy scheme with two identical sections that control only their corresponding nominal and redundant elements. The only exception to this is the dual-redundancy of the 1553 IF with the S/C and the DPU.

Internally, each section of the NI-ICU is organized in three boards.

- The LVPS (Low Voltage Power Supply) board features all the DC/DC converters necessary for the secondary power supplies internal to the NI-ICU. It also allocates the EMC filters so as to meet the electromagnetic compatibility requirements. Input voltage for this module comes directly from the primary 28V provided by the S/C. The LVPS shall not provide secondary power to any electronic unit external to the NI-ICU. This module also allocates one 1553 connector and transceiver.

- The CDPU (Central Data Processing Unit) board is based on the GPM (General Purpose Module) developed by Crisa, featuring a MDPA ASIC with a LEON2-FT processor, Memory banks, an RTAX-2000 FPGA, 1553 IF with the S/C and the DPU, Spacewire for inter-board communication and buffering and SPI master.

- The DAS (Driver and Acquisition Support) includes the electronic drivers for the mechanism, calibration lamps and heaters. It features a Secoia ASIC developed by Crisa, for PWM generation and analog acquisition.

In particular this board shall drive:

- 2 motor coils of the stepper motor of the cryo-mechanism that spins the filter and grism wheels
- 1 reference position sensor
- 2 heater lines, one for the opto-mechanical assembly, where the filters and grisms are allocated, the other for the focal plane array of the detectors. The heaters set point will be commanded from ground: no PID will be implemented on board the instrument.
- 5 LEDs of the calibration unit, controlled by PWM

This board must read next sensors:

- 12 temperature sensors PT-100: 6 in the opto-mechanical assembly, 4 in the detector system, and 2 in the cryo-mechanism

All boards will be connected through a backplane motherboard and will be custom-made for the NI-ICU.

This paper presents the NI-ICU status of definition and design at the end of the detailed design phase.

9904-233, Session PS8

Use of updated material properties in parametric optimization of spaceborne mirrors

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Spaceborne sensor mirrors need to be both structurally efficient and to maintain figure through thermal transients. Both properties can be represented in a plot showing structural efficiency (Young's Modulus divided by density) on one axis and thermal transient resilience (Thermal Diffusivity divided by Coefficient of Thermal Expansion) on the other. Such charts have been effectively used by optomechanical engineers for decades for preliminary material selection. However for several materials, the thermal attributes have improved considerably from those used in handbook charts. When contemporary values are used, this comparison chart looks differently. We will express this chart both at room temperature and at cooled temperatures, and look at the formulation of lines of equal merit. We will discuss how these lines of equal merit may be formulated differently depending on the orbit of the mission.

9904-234, Session PS8

Laboratory demonstration of a primary active mirror for space with the LATT: large aperture telescope technology

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The LATT project is an ESA contract to demonstrate the scalability of the technology from ground-based adaptive mirrors to space active primaries. A prototype spherical mirror based on a 40cm diameter thin glass shell with 19 contactless, voice-coil actuators and co-located position sensors has been manufactured and integrated, into a final unit with an areal density lower than 22kg/m2. Laboratory tests demonstrated the controllability with very low power budget and the survival of the fragile glass shell exposed to launch accelerations, thanks to an electrostatic locking procedure; such achievements pushes the technology readiness toward level 5.

Through such a prototype, the LATT project explored the feasibility of an active and lightweight primary for space telescopes. The concept is attractive for large segmented apertures, fitted with a surface active control to shape and co-phase them once in flight.

In this paper we will describe the findings of the technological advances and the results of the environmental and optical tests carried out on the prototype.

9904-235, Session PS8

Co-phasing primary mirror segments of an optical space telescope using a long stroke Zernike WFS: simulation and laboratory experiments

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Static Zernike phase-contrast plates have been used extensively in microscopy for half a century and, more recently, in optical telescopes for wavefront sensing. A dynamic Zernike wavefront sensor (WFS) with four phase shifts, for reducing error due to spurious light and eliminating other asynchronous noise, has been proposed for use in adaptive optics. Here, we propose adapting this method for co-phasing the primary mirror of a segmented space telescope. In order to extend the dynamic range of the WFS, which has a maximum range of +/- ? /2, a phase-contrast plate with multiple steps, both positive and negative, has been developed such that errors as large as +/-10? can be sensed. The manufacturing tolerances have been incorporated into simulations, which demonstrate that performance impacts are minimal. We show that the addition of this small optical plate along with a high precision linear translation stage at the prime focus of a telescope and pupil viewing capability can provide extremely accurate segment phasing with a simple white-light fringe fitting algorithm and a closed-loop controller. The original focal-plane geometry of a centro-symmetric phase shifting element is replaced with a much less constrained shape, such as a slot. Also, a dedicated pupil imager is not strictly required; an existing pupil sampler such as a Shack-Hartmann (SH) WFS can be used just as effectively, allowing simultaneous detection of wavefront errors using both intensity and spot positions on the SH-WFS. This could lead to an efficient synergy between Zernike and SH-WFS, enabling segment phasing in conjunction with high-dynamic range sensing.

9904-236, Session PS8

The satellite formation flying in lab: PROBA-3/ASPIICS metrology subsystems test-bed

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(Romania); Cédric Thizy, Jean-Sébastien Servaye, Etienne Renotte, Univ. de Liège (Belgium)

Formation flying is one of the most promising techniques for the future of astronomy and astrophysics from the space. The capabilities of the rockets strongly impact the dimensions and the weights of telescopes and instrumentation to be launched. Telescopes composed by several smallest satellites in formation flying, could be the key for build big space telescopes. With this aim, the ESA PROBA-3 mission will demonstrate the capabilities of this technology, maintaining two satellites aligned within 1 mm (longitudinal) when the nominal distance between the two is of around 144m. The scientific objective of the mission is the observation of the solar corona from 1.08 solar radii. The Coronagraph Spacecraft (CSC) will observe the Sun, when the second spacecraft, the Occulter Spacecraft (OSC) will work as an external occulter, eclipsing to the CSC the sun disk. The finest metrology sub-systems, the Shadow Position Sensors (SPS) and the Occulter Position Sensor Emitters (OPSE) identifying respectively the CSC-Sun axis and the formation flying (i.e., CSC-OSC) axis will be considered here. In particular this paper is dedicated to the test-bed for the characterization, the performance analysis and the algorithms capabilities analysis of the two metrology subsystems. The test-bed is able to simulate the different flight conditions of the two spacecrafts and will give the opportunity to check the response of the subsystems in the conditions as close as possible to the flight. The first data set relative to the ASPIICS SPS and OPSE demonstration models will be also discussed.

9904-237, Session PS8

CFRP mirror technology for cryogenic space interferometry: review and progress to date

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For optical designers to keep pace with the ambitions of the astronomy community, lighter, stiffer and more tailorable materials must be found and developed for telescope primary apertures. A telescope that is designed for far infrared observations requires stable optical performance over extreme temperature ranges. An interferometer with a pair of 2m diameter primary apertures is envisaged which will operate at 4K to eliminate back ground self-emission. The mass of the telescope must be kept to a minimum to enable payload mass for instrumentation and to limit cost of launching such a mission to an L2 orbit.

In partnership with the National Facility for Ultra Precision surfaces at OpTIC St Asaph and the Advanced Composites Training and Development centre in Broughton North Wales, Glyndwr University are developing the capability to create lightweight optical surfaces for a range of applications.

This paper focus' on the research and development of a Carbon Fibre Reinforced Plastic (CFRP) 2m primary for this for an FP7 project, FISICA (Far Infrared Space Interferometer Critical Assessment). In particular, we focus on the history of CFRP mirror technologies and the challenges the optical designers face when using anisotropic material for precision surfaces. We highlight the difficulty in the creation of a primary mirror that will operate in such a low temperature environment. One key aspect of this project was the lack of data for CFRP material properties at cryogenic temperatures. In collaboration with a FISICA partner at the University of Lethbridge, Alberta Canada, a test procedure was developed and the resulting coefficient of expansion properties, dominated by the fibre orientation was fed into an Abaqus Finite Element Analysis (FEA) model in order to ascertain the temporal rigidity of the mirror. A further complication during thermal cycling of samples was observed during the test in that the CTE of the material increased after each cycle. To quantify the effect and determine the cause of the issue an FEA was developed.

We conclude with a discussion of the research and development of this technology in order to raise the technology readiness level of CFRP mirrors for lightweight primary mirror space telescopes.

9904-238, Session PS8

Radiance from an ice-contaminated surface

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The formation of water ice on key thermal and optical surfaces is a consideration in the design and performance of the James Webb Space Telescope. Many of these concerns are related to the mid-infrared stray light and thermal performance of the system. In this paper, an expression for the radiance of a contaminated surface is formulated, including directional, film thickness and cooling effects. The resulting formula is then evaluated to show how radiance emanating from the surface changes for various thicknesses of the ice layer as a function wavelength and the local thermal environment. This paper concludes with an analysis and discussion of this complex behavior.

9904-239, Session PS8

A novel design of dual-channel optical system of star tracker based on non-blind area PAL system

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Star tracker plays an important role in satellite navigation, which is an optical device to control the attitude and orbit of satellite through capturing real-time images of stars, measuring the positions, and recalculating the motion orbit itself. Considering the satellites on near-Earth orbit, the star trackers usually have two optical systems: one for observing the profile of Earth and the other for capturing the positions of stars. However, the relatively heavy weight of two optical systems will result in an overmuch energy consumption for astronomical satellites. With the purpose of reducing the weight, we demonstrate a novel kind of dual-band optical structure of star tracker based on non-blind area PAL imaging system, which can combine both optical systems into an integrated one and realize the miniaturized design. Panoramic annular lens (PAL) consists of two refractive and two reflective surfaces, and is a kind of special optical system used for imaging the objects around the optical axis, that means the field of view (FOV) is large and centered at a plane orthogonal to optical axis. According to the imaging principle, PAL system can transform a 360° cylindrical FOV onto a two-dimensional annular plane. An inevitable problem of PAL is that the central part of its image plane cannot capture any ray and form a round blind area. In this paper, we try to make use of this round blind area and propose to design an additional correcting lens group in front of PAL system for making up the blind area and imaging the objects before this system. Dichroic filter is a kind of wavelength-based film, which can let some band refract and make some other band reflect. We substitute the conventional reflective film on reflective surfaces of PAL block by the dichroic filter of ultraviolet band reflected and visible band transmitted. Since the feature of this filter, we set the ultraviolet band as the PAL channel to observe the Earth with the FOV ranging from 40°-60°, and set the visible band as the front imaging channel with the FOV ranging from 0°-20° to capture the stars far away from this star tracker. Consequently, the rays of both channels are converged on the same image plane, improving the efficiency of pixels of detector. Obviously, because the UV channel is used to observe the Earth, the FOV of front imaging channel is obstructed, and there must be a mirror in front of the whole system to deflect the beam. As a result, the problem of blind area of PAL is solved and two optical systems are combined into an integrated one.

9904-240, Session PS8

Distortion of the pixel grid in WFC3/UVIS and ACS/WFC CCD detectors and its astrometric correction

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The geometric distortion of the CCD detectors used in the HST Wide Field Camera 3 (WFC3) and Advanced Camera for Surveys (ACS) instruments is characterized by both macro and micro-scale distortions. The macro-distortion owing to the tilt of the HST optical assembly is modeled as a high-order polynomial. The micro-distortion is inherent to the CCD detectors themselves which manifests as a fine-scale systematic offset in the residuals from the best-fit polynomial solutions. Such systematic errors with a complex spatial structure across the CCD chips introduce astrometric errors at the level of about 0.2 pix (up to 3 micrometers with the 15 micrometers per pixels). These fine-scale and low-amplitude distortions arise from spatial irregularities in the pixel grids. For the WFC3/UVIS CCD chips, there is clear pattern of a periodic skew in the lithographic-mask stencil imprinted on the detector. Similar irregularities in the pixel grid of ACS/WFC CCD chips are more pronounced and their origins not yet fully understood. To remove these micro-distortions, a 2-D correction in the form of look-up table is developed using the HST images of very dense fields of stellar clusters. The post-correction of fine-scale astrometric errors can be removed down to the level of 0.05 pix (0.75 micrometers) or better. Only space-borne observations are able to provide the necessary precision to detect this small systematics in the pixel grid.

9904-253, Session PS8

Battery-powered thin film deposition process for coating telescope mirrors in space

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An aluminum film manufactured in the vacuum of space may increase the broadband reflectance response of a space telescope operating in the EUV (50-nm to 115-nm) by eliminating absorbing metal-fluorides and/or metal-oxides, which typically reduce aluminum's reflectance below 115-nm and cut-off reflectance below ~90-nm. Recent developments in battery technology allow relatively large amounts of power to be discharged in a short period of time. It is therefore conceivable to power an array of resistive evaporation filaments in a space environment, using a reasonable mass of batteries and other supporting hardware. This technique may be advantageous for coating a large, broadband telescope mirror in space. This paper presents reflectance results, as well as, coating uniformity results, for aluminum films made using an array of battery-powered evaporation filaments, placed inside a vacuum chamber.

9904-242, Session PS9

Cryogenic proton irradiation of an EM-CCD for the WFIRST-AFTA coronagraph

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The Wide Field Infra-Red Survey Telescope (WFIRST) is a NASA observatory designed to perform wide-field surveys of the near-infrared sky and direct imaging of exoplanets in the visible. Of the two instruments on-board, a high contrast coronagraph will carry out the direct imaging and spectroscopic analysis of exoplanets, providing a means to probe the structure and composition of planetary systems.

Since the WFIRST coronagraph is expected to operate in low photon flux for long integration times, all noise sources must be kept to a minimum. The Electron Multiplication (EM)-CCD has been baselined for both the imaging and spectrograph cameras because of its low effective electronic read noise at sub-electron values with appropriate multiplication gain setting. The presence of other noise sources, however, such as thermal dark signal and Clock Induced Charge (CIC), need to be characterized and mitigated. In addition, operation within a space environment will subject the device to radiation damage that will degrade the Charge Transfer efficiency (CTE) of the device throughout the mission lifetime. Irradiation at the nominal instrument operating temperature has the potential to provide the best estimate of performance degradation that will be experienced in flight, since the final populations of silicon defects has been shown to have strong temperature dependence.

Here we present our latest results from pre-and post- cryogenic irradiation testing of the e2v CCD201-20 BI EM-CCD sensor, baselined for the WFIRST-AFTA coronagraph instrument.

9904-243, Session PS10

Zernike wavefront sensor (ZWFS) development for low order wavefront sensing (LOWFS)

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ZWFS measures phase via the phase-contrast method and is known to be photon noise optimal for measuring low order aberrations. Recently, ZWFS was selected as the baseline LOWFS technology on WFIST-AFTA for its good sensitivity, accuracy, and its easy integration with the starlight rejection mask. In this paper, we presents the ZWFS model validation experiment results from the fabricated ZWFS phase mask on a stand-alone LOWFS testbed and Palomar telescope.

9904-244, Session PS10

Sparse aperture mask wavefront sensor testbed results

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In any future space telescope outfitted for exoplanet imaging, and in particular in the Coronagraph Instrument (CGI) for WFIRST-AFTA, it will be necessary to estimate and control low-order wavefront aberrations to maintain the desired coronagraphic starlight suppression for exoplanet detection. At the Princeton High Contrast Imaging Lab (PHCIL), we are working on a new technique that integrates a sparse-aperture mask (SAM) with a shaped pupil coronagraph (SPC) to make precise estimations of these low-order aberrations. We collect the starlight rejected from the

coronagraphic image plane and interfere it using a sparse aperture mask (SAM) at the relay pupil to estimate the low-order aberrations. In our previous work, we have numerically proven the efficacy of this technique at broadband up to 50% and we have shown that we can control these aberrations below the desired level. We also presented the initial tilt results from our testbed, which was a work on progress. In this paper, we will briefly overview the SAM wavefront sensor technique, explain the design of the completed testbed, and report the experimental estimation results of the dominant low-order aberrations.

9904-245, Session PS10

Active damping of the TALC space telescope

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Further space exploration in the far-infrared requires larger telescopes, in order to improve the spatial resolution of captured images. To this purpose, several conceptual designs of future space telescopes are currently under study. One of them is the Thinned Aperture Light Collector (TALC). It consists of a 20 meter diameter deployable primary mirror, connected to a central boom through cables in tension in the manner of a bycle wheel. In the deployed configuration, structural vibrations need to be drastically reduced to collect the light.

In the first part of this paper, a dynamical model of the TALC telescope is presented, showing the modes shapes and typical structural responses. It is shown that resonances can be divided into global modes, e.g. primary miror ovalisation, and local modes, e.g. petal modes. Two control concepts are developed for damping actively these modes. The first one consists of actively modifying the tension of several cables, and the second one consists of actuating pistons placed at outer edge of petals. It is shown that the first concept is effective controlling global modes, while the second one is effective for controlling local modes. Both concepts use piezoelectric actuators, driven by robust decentralized control laws. The numerical study is completed by a parameter variation on the number/position of actuators in order to maximize the control authority with a limited number of actuators.

The second part of the paper is dedicated to an experimental validation of the proposed control concept on a 1/10 scaled prototype of tha TALC telescope. Compared to the full scale telescope, the prototype will not be deployabe, i.e. each miror segments will be connected to its neighbours through flexural hinges mimicing the kinematics of the deployed stage. Moreover, the mirors are made of aluminium honeycomb structures, and the overall mass of the optics is represented by a dummy mass attached at one end of the central carbon boom.

9904-246, Session PS10

Modeling of deformable mirror quilting orders

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Model-based wavefront control methods such as electric field conjugation require accurate optical propagation models to create high-contrast regions in the focal plane using deformable mirrors (DMs). Recently, it has been shown that it is possible to exceed the controllability outer-working angle imposed by the Nyquist limit based on the number of actuators by utilizing a diffraction grating. The print-through pattern on MEMS-based DMs formed during the fabrication process creates both an amplitude and a phase diffraction grating that can be used to enable Super-Nyquist wavefront control. Using high-resolution interferometric measurements of a DM-actuator, we develop a DM-diffraction grating model. We evaluate the accuracy of the model by comparison of the location and strength of the quilting orders from model predictions with experimental measurements obtained from the ACE laboratory.

9904-247, Session PS10

Active structural vibration control for high-performance space optical payload

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Optical performance of high resolution space camera is severely affected by micro-vibration induced by bus disturbances, such as reaction wheel assembly (RWA), control moment gyroscope (CMG), thrusters, stepper motors, cryo-coolers, solar array drives, thermal popping, etc. As a result, vibration isolation is commonly required. The first step taken to settle this issue is often passive mechanical isolation because it is simple and reliable. For cases that the disturbance sources are excessive to the payload and the performance requirement cannot be met using passive isolators alone, additional steps like active control are taken. Recently, hybrid (passive/active) and active vibration isolation systems have been investigated broadly and demonstrated on orbit.

This paper proposed an active vibration isolation platform (AVIP) for a new agile remote sensing satellite. Agility means this satellite can acquire off-nadir scenes rapidly in a large flight envelope in the same orbit, and, at the meantime, requires very precise pointing during the exposure periods. The proposed AVIP consists of six voice coil legs with integral load cells (for feedback control). In every leg, the cylinder permanent magnet of the voice coil actuator is fixed on the base plate, with a membrane mounted inside, which is the main contributor to the axial compliance of the leg. The stinger is attached to the center of the membranes, supporting the voice coil at one end, and attaching to force sensor at the other end. One flexible joint is used to connect the leg, respectively to the base plate and to the payload plate. These six legs are arranged in a cubic Stewart platform configuration, which provides a uniform control capability and a uniform stiffness in all directions, and minimizes the crosscoupling amongst actuators and sensors of different legs. In addition, the AVIP includes gap sensors and payload side accelerometers for measurement.

An integrated framework consisting of disturbances, structure, optics, the AVIP, and their mutual interactions is created to evaluate the performance of the AVIP through numerical simulation. The disturbance data is collected by sensors located on the deck that the payload is mounted to the satellite bus in a ground-test with actuating components operating and the satellite suspended. The analysis shows that the AVIP is effective in a frequency band between 10 and 400 Hz, with a attenuation of not less than 20 dB, and proves that the AVIP is able to keep the payload in step with the bus in the course of agile imaging. An experimental test system is built on the AVIP, an optical payload, advanced multi-axis micro-vibration table, and suspension devices. The advanced multi-axis micro-vibration table is also a Stewart platform containing six voice coil legs but much bigger. Besides the calibrated accelerometers equipped to measure the transmissibility, a laser interferometer is implemented in order to measure the pointing precision of the optical payload. Result of experiment shows close agreement with that of the simulation.

9904-248, Session PS10

Unimorph piezoelectric deformable mirrors for space telescopes

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Under the GSTP activity "Development of Adaptive Deformable Mirrors for Space Instruments", funded by the European Space Agency, we have developed, manufactured and tested a space-qualified unimorph deformable mirror. The goal was a generic technology development for a deformable mirror that would be used in a plane conjugate to the primary mirror of a large space telescope. The mirror we developed can be readily adapted to suite different space telescopes. For example, the mirror could be made annular such that its deformation eigenmodes resemble that of a large monolithic primary mirror. For a telescope with a segmented primary mirror, a segmented array of unimorph deformable mirrors could be designed, such that each segment of the primary mirror is imaged onto one unimorph deformable mirror. With additional piston and tip-tilt actuation, this array of unimorph mirrors could provide phasing and aberration correction of the segments of the primary mirror. This approach moves the complexity of active optics to scales where they are easier to manage: away from the large primary to a smaller mirror that needs less actuation force, has a higher temporal bandwidth, and operates in a thermally stable environment inside the telescope.

For the generic technology development, ESA had called for a mirror that had to generate low order Zernike modes with a fairly large peak-to-valley (PV) surface stroke of 30 μm in defocus mode (60 μm PV wavefront), and 5 μm PV surface stroke in trefoil mode over a clear aperture of 50 mm. The modes had to be produced with a residual RMS surface error below 30 nm. The active structure of our mirror consists of a coated mirror substrate bonded to a laser-cut piezoelectric element featuring 44 actuators. The innovative mounting allows for large stroke while at the same time providing rigid connection to the support structure. In addition, the mounting incorporates three actuators providing integrated, monolithic piston and tip/tilt functionalities. Since the mirror is based on just a few, precisely CTE-matched materials, it is insensitive to temperature fluctuations.

High spatial frequency deformations caused by the actuators, commonly referred to as print-through, is a common problem for many deformable mirrors. By suitable pre-treatment of the piezoelectric material and careful control of the manufacturing procedure, we were able to eliminate print-through to a level below 17 nm.

The mirror was successfully tested in thermal vacuum, underwent a lifetime test, and was exposed to random vibrations, sinusoidal vibrations, and to ionizing radiation. The mirror was successfully operated in thermal vacuum at 300 K, 200 K, and 100 K. It withstood sine vibration up to 20 g and random vibration loads up to 9.3 g RMS. This should render the mirror compliant to common launch vehicles. The most recent design iteration has been further optimized to provide increased resistance towards vibrations by shifting the first eigenfrequency from 253 Hz for the tested design to about 600 Hz. The optical performance has been validated by high-resolution phase shifting interferometry and the dynamic response was characterized using a fast Shack-Hartmann wavefront sensor.

9904-249, Session PS10

Hypatia and STOIC: an active optics system for a large space telescope

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The next generation of UVOIR space telescopes will be required to provide excellent wavefront control despite perturbations due to thermal changes, gravity release and vibrations. The STOIC project is a response to an ESA Invitation to Tender to develop an active optics correction chain for future space telescopes. The baseline space telescope being considered is a two-mirror, 4m telescope with a monolithic primary mirror – we refer to this concept as Hypatia. The primary mirror diameter could be extended, but is limited in the near future by launch vehicle dimensions. A deformable mirror (diameter 100mm) will be an integral part of the telescope design; it is being designed for high precision and the ability to maintain a stable form over long periods of time. We demonstrate our approach to design a set-and-forget deformable mirror that is suitable for space missions positioned in L2, where no fast wavefront deformations have to be corrected, but where reliability and long-term stability are critical. The concept is based on rotary piezoLEG actuators that are self-locking and can therefore hold the position without a continuous power supply. We present an extensive study on the possible actuator positions to find the best distribution in order to correct even high-order Zernike modes with a minimized number of actuators.

The secondary mirror of the telescope will be activated to control tip-tilt, defocus and alignment with the primary. Wavefront sensing will be based on phase diversity and a dedicated Shack-Hartmann wavefront sensor. A tomographic approach is proposed to distinguish aberrations due to telescope misalignment from those due to errors in the primary mirror.

The project will develop a laboratory breadboard to demonstrate key aspects of the active correction chain. We present the current state of the preliminary design for both the Hypatia space telescope and the laboratory breadboard.

9904-250, Session PS10

High dynamic range wavefront sensing for large aperture space telescopes

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For large aperture space telescopes, end-to-end optical performance testing is rarely performed after system integration. Significant gravity-induced aberrations often prohibit the use of traditional interferometric techniques, and design constraints do not typically accommodate supplemental test instruments. In this paper we present a high dynamic range wavefront sensing approach to accurately assess telescope performance in the presence of large aberrations, such as the gravity sag of a primary mirror. The approach uses the payload imaging system directly, eliminating the need for an additional scoring instrument or non-common-path calibration. First, the pupil is divided into overlapping subapertures to reduce the wavefront aberration presented to the sensing algorithms. A parametric image-matching algorithm (IPO) is applied to images taken over each subaperture to obtain a low-spatial-resolution estimate of the wavefront error. The result forms an a priori estimate for Modified Gerchberg-Saxton (MGS), a non-parametric phase retrieval algorithm that uses defocused image pairs to produce a final, high-resolution wavefront map over the subaperture. Finally, a least squares stitching algorithm is employed to assemble the subaperture wavefront estimates into the complete pupil. Simulation results demonstrating sensing performance are presented in the context of the 2.4 meter WFIRST-AFTA telescope.

9904-252, Session PS10

Wavefront sensing in space from the PICTURE-B sounding rocket

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NASA sounding rocket for high contrast imaging with a visible nulling coronagraph the Planet Imaging Coronagraphic Technology Using a Reconfigurable Experimental Base (PICTURE-B) mission has made two suborbital attempts to observe the warm dust disk inferred around Epsilon Eridani.

We present results from the November 2015 launch demonstrating active wavefront sensing in space with a piezoelectric mirror stage and a deformable mirror along with precision pointing and lightweight optics in space. We also discuss the testing of a new half-meter silicon carbide primary mirror for the most recent launch and lessons learned translating coronagraphy concepts into spaceflight hardware.

9904-45, Session 12

Ensuring the enduring viability of the space science enterprise: new questions, new thinking, new paradigms

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Pursuing ground breaking science in a highly cost and funding constrained environment presents new challenges to the development of future space astrophysics missions. Within the conventional cost models for large observatories, executing a flagship “mission after next” appears to be unstainable. To achieve our nation’s space astrophysics ambitions requires new paradigms in system design, development and manufacture. Implementation of this new paradigm requires that the space astrophysics community adopt new answers to a new set of questions. This paper will discuss the origins of these new questions and the steps to their answers.

9904-46, Session 12

Risk management for small to mid-sized spaceborne telescopes

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For proposed missions, perceived risk levels often leads large margins of safety. This affects both what telescope aperture the Science Team will propose, and what Proposal Evaluators will accept. Too often the appropriate cost of the telescope and even the mission is evaluated largely on the basis of aperture. While aperture clearly is a factor in telescope cost, it is not the only one. This paper will explore some basic and early architecture decisions that may have a profound effect on both the risk and cost of a telescope. Starting with the system’s risk and cost impact of choice of materials, factors including performance margins and management of envelope will be considered. Emphasis is on small to mid-sized optical telescope assemblies relevant for Explorer and Probe class missions.

9904-47, Session 12

Configurable aperture space telescope (CAST) optical design

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CAST, the Configurable Aperture Space Telescope, is a concept that provides access to an ultraviolet/visible-wavelength sub-arcsecond imaging platform from space, something that will be in high demand after the retirement of the astronomy workhorse, the 2.4 meter diameter Hubble Space Telescope. CAST is a concept that allows building large aperture telescopes based on small, compatible and low-cost segments mounted on autonomous cube-sized satellites. The concept merges existing technology (segmented telescope architecture) with emerging technology (smartly interconnected modular spacecraft). Requiring identical mirror segments, CAST’s optical design is a spherical primary and secondary mirror telescope with a modular three-mirror corrector placed at the system focal plane. The design enables very wide fields of view, up to as much as three degrees, while maintaining aperture growth and image performance requirements. CAST with a 0.6 meter diameter primary (3x3 segments) growing to 2.4 meter diameter (13x13 segments), with a fixed Rp=14,000 and Rs=8,750 mm curvature, yields f/22.4 and f/5.6, respectively. Its diffraction-limited design uses a two arcmin field-of-view corrector with a 7.4 arcsec/mm platescale, and can support a range of platescales as fine as 0.01 arcsec/mm. Our paper summarizes the CAST concept, presents the strawman optical design and requirements for the underlying modular spacecraft, and illustrates applications enabled by this new method in building space observatories.

9904-48, Session 12

APERTURE: a precise extremely large reflective telescope using re-configurable elements

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One of the pressing needs for the UV-Vis is a design to allow even larger mirrors than the JWST primary at an affordable cost. We report here the results of NASA Innovative Advanced Concepts phase 1 study. Our project is called A Precise Extremely large Reflective Telescope Using Reconfigurable Elements (APERTURE).

The idea is to deploy a membrane-like mirror. The mirror figure will be corrected after deployment to bring it into better or equal lambda/20 deviations from the prescribed mirror shape. The basic concept is not new. What is new is to use a different approach from the classical piezoelectric-patch technology. Instead, our concept is based on a continuous coating of a so called magnetic smart material (MSM). Then a magnetic write head will on the no reflecting side of the mirror insert magnetic field that will produce a stress in the MSM that will correct the mirror deviations from the prescribed shape.

9904-49, Session 12

ASTRO-1: a 1.8m unobscured space observatory for next generation UV/visible astrophysics and exoplanet exploration

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The Hubble Space Telescope has been a scientific marvel that has provided unimaginable imagery and scientific discovery. Its exquisite UV/Visible imaging performance is unmatched from the ground. In NASA’s future planning, the earliest possible successor mission would be in the 3030s, well beyond the expected lifetime of Hubble. The ASTRO-1 space telescope

is a 1.8m off-axis (unobscured) observatory that looks to fill this critical void with Hubble-like performance to continue the scientific quest while also providing the possibility for exoplanet research with a coronagraphic instrument and/or a free flying starshade. BoldlyGo Institute seeks to reach beyond NASA funding to leverage the high public interest in space research and exploration, and the search for life beyond Earth.

9904-50, Session 13

Optical telescope system-level design considerations for a space-based gravitational wave mission

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The study of the Universe through gravitational waves will yield a revolutionary new perspective on the Universe, which has been intensely studied using electromagnetic signals in many wavelength bands. Gravitational interactions dominate the behavior of systems and structures at the largest length scales. Those interactions are traceable with gravitational waves to much higher redshift ($z \approx 20$) than is possible with electromagnetic signals. A space-based gravitational wave observatory will enable access to a rich array of astrophysical sources in the measurement band from 0.1 to 100 mHz, and nicely complement observations from ground-based detectors as well as pulsar timing arrays by sampling a different range of compact object masses and astrophysical processes.

This observatory measures gravitational radiation by precisely monitoring the tiny change in the proper distance between pairs of freely falling proof masses. These masses are separated by millions of kilometers and, using a laser heterodyne interferometric technique, the change in their proper separation is detected to ~ 10 pm over timescales of 1000 seconds, a fractional precision of better than one part in 1019. Optical telescopes are essential for the implementation of this precision displacement measurement. They enable the efficient transfer of laser beams between the proof masses, but are then in-series with the measurement path. This role, quite different from image-forming telescopes, is the inherent drive behind the design of the telescope subsystem, and produces interesting design constraints that we will discuss.

We also focus our discussion towards the telescope subsystem in a mission context. We will review the flow-down of observatory level requirements to the telescope subsystem, particularly pertaining to the effects of telescopic dimensional stability and scattered light suppression on the interferometric measurement. Furthermore, we will discuss how this consideration impacts the telescope form, and also review the telescope's function in an on-orbit science-mode state. We analyze all these topics in the context of the enhanced Laser Interferometry Space Antenna mission (eLISA), a strong candidate for the European Space Agency's L3 launch opportunity in 2034. Finally, we present a nominal timeline of the telescope subsystem as we embark upon preparations for the eventual study of gravitational waves using a space-based observatory.

9904-51, Session 13

A development roadmap for critical technologies needed for TALC: a deployable 20m annular space telescope

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Astronomy is driven by the quest for higher sensitivity and improved angular resolution in order to detect fainter or smaller objects. The far-infrared to submillimeter domain is a unique probe of the cold and obscured Universe, harboring for instance the precious signatures of key elements such as water. Space observations are mandatory given the blocking effect of our atmosphere. However the methods we have relied on so far to develop increasingly larger telescopes are now reaching a hard limit, with the JWST illustrating it in more than one way (e.g. it will be launched by one of the most powerful rocket, it requires the largest existing facility on Earth to be qualified). With the Thinned Aperture Light Collector (TALC) project, a concept of a deployable 20m annular telescope, we propose to break out of this deadlock by developing novel technologies for space telescopes, which are disruptive in three aspects:

- An innovative deployable mirror whose topology, based on stacking rather than folding, leading to an optimum ratio of collecting area over volume, creates a telescope with an eight times larger collecting area and three times higher angular resolution compared to JWST from the same pre-deployed volume; ?

- An ultra-light weight segmented primary mirror, based on electrodeposit Nickel, Composite and Honeycomb stacks, built with a replica process to control costs and mitigate the industrial risks.

- An active optics control layer based on piezo-electric layers incorporated into the mirror rear shell allowing controlling the shape by internal stress rather than by reaction on a structure.

We present in this paper the roadmap we have built to bring these three disruptive technologies to technology readiness level 3. We will achieve this goal through design and realization of representative elements: segment of mirrors for optical quality verification, active optics implemented on representative mirror stacks to characterize the shape correction capabilities, and mechanical models for validation of the deployment concept. Throughout the project, a strong system activity will ensure that the ultimate goal of having an integrated system can be met, especially in terms of (a) scalability toward a larger structure, and (b) verification philosophy.

9904-52, Session 13

Millimetron space observatory: progress in the development of the payload module

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Previous and future FIR and submm space observatories have respectively inspired and promised a new outlook in our understanding of key questions in modern astrophysics. The future Millimetron Space Observatory (MSO) is based on a 10-m cryogenically cooled telescope, to be deployed in orbit after having arrived at a L2 orbit of the Earth-Sun system. The MSO will operate as a single aperture enabling high-resolution imaging and spectroscopy but also as an interferometer element in a Space-Earth VLBI regime and as such will open up new horizons of astrophysics with unprecedented sub-microarcsecond angular resolution.

The MSO will be launched at ambient temperatures and cooled down in orbit through a combination of passive and active cooling using on-board mechanical coolers. These provides cooling of the 10-m space telescope to temperatures below 10K and thus reduce by five orders of magnitude the thermal background emission from the entrance optics and thus improve the sensitivity to a level which has been unobtainable so far. MSO instruments will include a FIR photometric camera spectrometers and mm/submm receivers for interferometry. The MSO is proposed as a Russian-led mission with an extensive international consortium. The launch is foreseen for the early 2025's. Ongoing detailed analysis and verification are essential to ensure that the requirements are met. We will present an overview and progress in the development of the payload module.

9904-53, Session 14

SEL2 servicing: increased science return via on-orbit propellant replenishment

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Amongst the challenges in reach for the next generation of astrophysics missions is the direct detection of exo-Earth atmospheres. These future observatories must have tremendous sensitivity, resolution and stability. The latter will drive many observatories to Sun-Earth Lagrange point 2 (SEL2). The mass fraction dedicated to propellant for these assets will need to be allocated strategically, as it comes at the expense of instrument mass. As such, these observatories could benefit from on-orbit refueling, allowing greater dry-to-wet mass ratio at launch. The same holds true for a separate starshade spacecraft used in tandem with an observatory to externally occult starlight. Given their position many thousands of kilometers away from their observatory, every slew to a new target would require a proportional translation of the starshade. The accumulation of repeated translations would drive the delta-V and therefore the propellant mass. Even if the starshade were equipped with high-efficiency solar electric propulsion systems using xenon (Xe), a propellant-based end of life would most likely occur while the corresponding observatory is still fully operational. Moreover, complete expenditure of the observatory's chemical propellant supply will inevitably cause cessation of operation, as SEL2 orbit maintenance requires constant fuel expenditure.

The Satellite Servicing Capabilities Office (SSCO) at NASA's Goddard Space Flight Center is developing technologies and techniques to replenish Xe and chemical propellant on orbit. Since 2009, SSCO has been building a portfolio of critical and enabling servicing technologies, including dexterous robotics; sensors, avionics, and algorithms for rendezvous and proximity operations; high-speed, fault-tolerant computing; advanced robotic tools; propellant transfer systems; and cooperative servicing aids such as navigation aids, grapple features, replacement hardware latches, and fueling ports. The Robotic Refueling Mission (2011-2019) and Raven (2016-2018) on the International Space Station are demonstrating some of these capabilities on orbit. Other technologies are being tested on the ground via tests such as the Remote Robotic Oxidizer Transfer Test (2014). In parallel, SSCO has spent five years designing a notional servicing mission named Restore-L, a free-flying robotic servicer to chemically refuel a government satellite in low-Earth orbit. By the time SEL2 observatories are launched in the late 2020s, it is expected that all the enabling servicing technologies listed above will have flight heritage and be at Technology Readiness Level 8 or higher.

This paper will detail a conceptual mission design for an autonomous, robotic servicer spacecraft equipped to execute a two-sortie mission at SEL2 to extend the life of an observatory and its accompanying starshade. After recharging the Xe of the starshade, it would refuel the chemical propellant of the observatory. We will discuss the concept of operations for this two-phase mission, the servicing spacecraft design, and the cooperative servicing elements assumed to be integrated within the two clients. We will also address key mission drivers, such as servicer autonomy (necessitated due to communications latency at L2), the need to minimize initial mass impacts on the client spacecraft, and multi-sortie mission features. We hope to spur symbiotic discussions and developments to better understand the science communities' requirements, and to implement cooperative servicing elements into future missions.

9904-54, Session 14

In-space assembly and servicing infrastructures for the Evolvable Space Telescope (EST)

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The concepts for the EST provided elsewhere in this conference stand to benefit significantly from developments in in-space infrastructures now being planned and implements in support of NASA's Human Exploration plans. Among others, two documents provide particularly relevant discussions. "NASA's Journey to Mars: Pioneering Next Steps in Space Exploration" provides a recent (2015) outline of NASA thinking on human deep space exploration and the tools that will enable it, while the "On-Orbit Satellite Servicing Study: Project Report" details a few of the concepts and technologies that must be developed.

This presentation will examine the concepts in these and related documents to explore how they can best exploit the developments described therein and how systems such as EST will add credibility and support to the infrastructure needed by human exploration programs. Major topics to be addressed will include:

• Past experience with on-orbit servicing of space telescopes, notably the Hubble Space Telescope, and demonstration of the benefits that it provided. Lessons learned concerning servicing approaches both under routine maintenance conditions and when time-urgent, mission critical needs apply, and existing systems and facilities both to prepare for and execute servicing missions in the future will be described.

• Developing plans within NASA for the SLS class of heavy lift launch vehicles, notably including the Exploration Upper Stage (EUS) which may be able to co-manifest other large payloads along with a crewed Orion mission. Commercial launch vehicles will also be considered in the presentation.

• The use of crewable Deep Space Habitats (DSHs) in cislunar space as assembly and servicing bases for space telescopes as well as human exploration missions will be comparatively discussed, with similarities and differences noted (as well as synergies among them).

• Maneuverable servicing vehicles for the assembly and servicing missions, either in the vicinity of crewed bases or on autonomous missions to deep space locations of the space telescopes themselves.

• Adaptations to the serviced space telescopes that will be needed to enable servicing (such as commonality of parts and systems, modularity, accessibility, and stable maneuverability) will also be discussed.

9904-55, Session 15

FalconSAT-7: a membrane space telescope

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The USAF Academy Department of Physics has built FalconSAT-7, a membrane solar telescope to be deployed from a 3U CubeSat in LEO. The primary optic is a 0.2m photon sieve – a diffractive element consisting of billions of tiny circular dimples etched into a Kapton sheet. The membrane, its support structure, secondary optics, two imaging cameras and associated control/recording electronics are all packaged within half

the CubeSat volume. Once in space the supporting pantograph structure is deployed, extending out and pulling the membrane flat under tension. The telescope will then be directed at the Sun to gather images at H-alpha for transmission to the ground. We will present details of the optical configuration, operation and performance of the flight telescope which has been made ready for launch in late 2016.

9904-56, Session 15

The Australian space eye: studying the history of galaxy formation with a CubeSat

Anthony J. Horton, Australian Astronomical Observatory (Australia); Lee R. Spitler, Macquarie Univ. (Australia); Naomi Mathers, The Australian National Univ. (Australia); Roger Franzen, Research School of Astronomy & Astrophysics (Australia); Mike Petkovic, The Australian National Univ. (Australia); Sam Reisenfeld, Macquarie Univ. (Australia); Jonathon S. Lawrence, Julia Tims, Australian Astronomical Observatory (Australia)

The Australian Space Eye is a proposed astronomical telescope based on a 6U CubeSat platform. The Space Eye will exploit the low level of systematic errors achievable with a small space based telescope to enable high accuracy measurements of extragalactic background light anisotropies and low surface brightness emission around nearby galaxies. This project is also a demonstrator for several technologies with general applicability to astronomical observations from nanosatellites.

Scientific opportunities for nanosatellite space telescopes exist where measurements are typically limited by systematic errors rather than photon statistics. We propose to undertake a study of extragalactic background light anisotropies, exploiting the low levels of systematic errors achievable with small space based telescopes. The power spectrum of these spatial anisotropies contains a signature of the population of objects too faint to be detected individually. This includes high redshift galaxies whose existence is inferred from the timing of the epoch of reionisation. Measurements from Space Eye will complement those obtained and planned from the CIBER/CIBER2 sounding rocket experiments which will cover a wider wavelength range but which are limited by the short duration of sounding rocket flights and aspects of the CIBER2 telescope design. We will also look for the signatures of galaxy growth in low surface brightness structures around several nearby galaxies, complementing shorter wavelength data from ground-based facilities (e.g. Dragonfly Telephoto Array).

The Australian Space Eye is based around a 90 mm aperture telescope for broadband wide field imaging in the i' and z' bands (700-1050 nm). The use of an e2V CIS115 2000x1504 CMOS image sensor with small (7 micron) pixels allows the desired 3 arcseconds/pixel image scale to be achieved within the space constraints of the CubeSat without folding the light path, enabling the use of a clear aperture all refractive design optimised to minimise the wings of the point spread function. The field of view is 1.67 x 1.25 degrees. The spacecraft will be based on the high performance Endeavour platform developed by Tyvac Nanosatellite Systems Inc. The largest technical challenges are pointing stability, data downlink and thermal control. No commercially available CubeSat attitude determination and control systems are able to achieve the arcsecond level instrument pointing stability required for long exposures, we present a solution combining high precision star tracking in the science telescope focal plane with microthruster based attitude control. Downlinking the anticipated science data volume of 400 MB per day will be a challenge however our analysis concludes that it is possible using currently available equipment. For maximum sensitivity the science image sensor must be cooled to -40C, this will be achieved with passive cooling and stabilised using a low power Peltier device.

The Australian Space Eye concept has been developed by Macquarie University, the Australian Astronomical Observatory, the Australian National University and Tyvac Nanosatellite Systems Inc. We aim to launch into a Sun synchronous orbit in 2019 for a nominal 2 year mission.

9904-57, Session 15

Image processing in BRITE nano-satellite mission

Adam Popowicz, Silesian Univ. of Technology (Poland)

Brightest Star Explorer (BRITE) is the first Polish astronomical satellite mission carried out by Polish-Austrian-Candian consortium. The constellation of 5 nano-satellites has been created and lunched to observe the micro variability of the brightest stars intensity. Each satellite has a CCD sensor installed onboard which is employed to observe the objects through either red or blue filter. The lack of the atmosphere allows for unprecedented high photometric precision, not achievable from the ground.

Unfortunately, due to the weight and space constraints in such small satellites, the installation of heavy shielding and employing strong sensor cooling was impossible. Thereby, shortly after the lunch, the radiation induced defects appeared in CCDs making the image analysis a difficult task. The defects are visible as significantly brighter pixels, column intensity offsets and charge transfer inefficiency regions. Those problems not only affect the scientific camera, but also the star tracker sensor. As a result, the satellite suffers from temporal instabilities, thus the images are occasionally blurred and the objects move within the CCD plane from frame to frame.

In the paper, the pipeline currently established for BRITE images processing is presented. The algorithm is divided into three main parts, which include the data classification, image processing and parameters optimization.

In the first part, the images are divided into three groups: faulty, correct and dark frame candidates. While the ones from the first set are discarded from further analysis, the dark frames, obtained by intentional satellite rotations, are utilized for hot pixels identification. The chosen best classification approach involves the manual thresholding of detected star PSF area.

The second part of the pipeline is the main photometric routine, wherein the star flux is retrieved. In this section, the column offsets, originating from the readout dark current, are first compensated. Then, the PSF region is detected and initial estimation of star centroid is obtained. For this purpose, the detected hot pixels within the PSF are temporally replaced by the median of intensities of neighbouring pixels. With initial centroids positions obtained, the precise estimation of true intensities of hot pixels is calculated. It is done by the analysis of the corresponding PSF pixels in previous and following frames in the orbit. This approach utilizes the fact that the satellite stabilization is low thus star PSF changes its position within CCD plane. The final part of this stage includes the classic circular aperture photometry on processed images.

The last part of the algorithm is the optimization loop which allows for the fine tuning of outcomes by adjusting the threshold level for hot pixel identification and a radius employed in aperture photometry. The spread of results in each orbit is calculated and used as a final quality meter.

The presented algorithm was developed especially for a wide range of defects encountered in BRITE CCDs. Since it allowed for achieving high precision photometry in significantly disturbed images, it may be a vital solution for future mission of nano-satellites, for which the radiation induced noise limits the measurements accuracy.

9904-58, Session 16

The maturing of high contrast starlight suppression techniques for future NASA exoplanet characterization missions

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It has been almost a quarter of a century since the discovery of the first planets beyond our own solar system, so called exoplanets, and 20 years since the discovery and confirmation of 51 Peg b, the first such object discovered orbiting a main-sequence star. Since that time, over 3000 exoplanets and hundreds of exoplanetary systems have been detected primarily by the ground based radial velocity technique and ground and space based microlensing and transit studies including NASA's spectacularly successful Kepler Mission. We are now rapidly moving toward an era where the focus is shifting from detection to spectroscopic characterization of these new worlds and their atmospheres, and to that end, NASA is currently studying exoplanet characterization mission concepts for the 2020 Decadal Survey ranging from probe class to flagships. Some low-resolution spectral data on exoplanet atmospheres has been collected with the Hubble Space Telescope and the Spitzer Space Telescope using the Transit Spectroscopy technique and more is expected from JWST. In addition, the JWST NIRCAM instrument will also carry a moderate contrast coronagraph capable of imaging large exoplanets and debris disks. However, a more detailed and comprehensive exoplanet characterization leading to assessment of habitability, or indeed detection of life, will require studies with higher contrast and improved spectral resolution and sensitivity. This will be possible due to the significant advances being made in high contrast starlight suppression techniques utilizing specially shaped precision optical elements to block the light from the parent star while controlling scattering and diffraction thus revealing and enabling spectroscopic study of the orbiting exoplanets in reflected light. In this paper we describe the current status of the two primary high contrast starlight suppression techniques: 1) a coronagraph (including several of its design variations) and 2) a free flying starshade. These techniques are rapidly moving from the technology development phase to the design and engineering phase and we discuss the prospects and projected performance for future exoplanet characterization missions utilizing these techniques coupled with a moderate to large aperture space telescope.

9904-59, Session 16

A comparison of analytical depth of search metrics with mission simulations for exoplanet imagers

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While new, advanced, ground-based instrumentation continues to produce new exoplanet discoveries and provide further insights into exoplanet formation and evolution, our desire to discover and characterize planets of Earth size about stars of all types and ages necessitates dedicated, imaging space instruments. Given the high costs and complexities of space observatories, it is vital to build confidence in a proposed instrument's capabilities during its design phase, and much effort has been devoted to predicting the performance of various flavors of space-based exoplanet imagers. The fundamental problem with trying to answer the question of how many exoplanets a given instrument will discover is that the number of discoverable planets is unknown, and so all results are entirely dependent on the assumptions made about the population of planets being studied. Here, we present an alternate approach, which involves explicitly separating instrumental and mission biasing from the assumptions made about planet distributions. This allows us to calculate a mission's 'depth of search'-a metric independent of the planetary population and defined as the fraction of the contrast--projected separation space reached by a given instrument for a fixed planetary radius and semi-major axis. When multiplied by an assumed occurrence rate for planets at this radius and semi-major axis (derived from an assumed planetary population), this yields the expected number of detections by the instrument for that population. Integrating over the full ranges of semi-major axis and planetary radius provides estimates of planet yield for a full mission. We use this metric to evaluate a variety of proposed space missions, including various coronagraphs under development for WFIRST-AFTA. We also compare the results of convolving the depth of search with an assumed planetary population to those derived by running full mission simulations based on that same population.

9904-60, Session 16

A direct comparison of exoEarth yields for starshades and coronagraphs

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The scale and design of a future mission capable of directly imaging extrasolar planets will be influenced by the expected number of potentially Earth-like planets (exoEarth candidates) to be detected and characterized. Currently two types of high-contrast imaging instruments, coronagraphs and starshades, are being considered for such a mission. These two types of instruments both remove stellar light, enabling the detection of faint planets nearby, but operate in different regimes and are ultimately limited by different resources. We have developed a code capable of estimating yields for both starshades and coronagraphs. This code uses novel methods to optimize the observation plan and maximize the yield of exoEarth candidates for a given set of mission parameters. We will present direct comparisons of yields for starshade-based missions and coronagraph-based missions, adopting identical astrophysical assumptions, methods of calculation, mission parameters, and observational assumptions when possible. We will show yield scaling relationships for each mission type and discuss the impact of astrophysical and instrumental noise on expected yields. Although the absolute yields are dependent on yet-unknown engineering constraints, observational methods, and astrophysical parameters, we will present several limiting cases allowing us to bound the yield comparison.

9904-61, Session 16

All clear: exoplanet detection and characterization with an unobscured 2.4 m aperture space telescope

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After completing a study on the capabilities of an unobscured 1.4-meter aperture telescope dedicated to exoplanet detection and characterization [1], the NASA Exoplanet Science and Technology Definition Team for internal coronagraphs (Exo-C) has analyzed how increasing D to a 2.4-meter diameter aperture, with appropriate increases in budgeted cost and schedule, impacts exoplanet direct imaging mission scientific goals and feasibility. Mission goals are aligned with the ability to characterize super-Earths within the habitable zone of Sun-like stars, with a raw contrast of 10^-10 and stability of 10^-11 at an inner working angle (IWA) of 2 lambda/D at visible wavelengths. Our approach is to minimize modifications needed to the original Exo-C instrument, telescope, and spacecraft to support the larger aperture. We also consider the benefits of including secondary science payloads, such as a near-infrared coronagraph that overlaps the longest visible wavelength bands and improves characterization of broad features such as water. We include analysis of mission scientific yield in the new 2.4-meter configuration, and recommend technology development to enable realization of this design by the early 2020s.

[1] Exo-C final report, https://exep.jpl.nasa.gov/stdt/Exo-C_Final_Report_for_Unlimited_Release_150323.pdf

9904-62, Session 16

ESA M4 mission candidate ARIEL

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The Atmospheric Remote sensing Infrared Exoplanet Large survey (ARIEL) mission is an M-class mission candidate within the science program Cosmic Vision of the European Space Agency (ESA). It was selected in June 2015 as one of three candidates to enter an assessment phase (phase 0/A). This process involves the definition of science and mission requirements as well as a preliminary model payload, and an internal Concurrent Design Facility (CDF) study providing the input to parallel industrial studies (to be conducted in 2016). After this process, the three candidates will be reviewed and in mid-2017 one of them will be selected as the M4 mission for launch in 2026.

ARIEL is a survey-type mission dedicated to the characterisation of exoplanetary atmospheres. Using the differential technique of transit spectroscopy, ARIEL will obtain transmission and/or emission spectra of the atmospheres of a large and diverse sample of known exoplanets (≥ 500) covering a wide range of masses, densities, equilibrium temperatures, orbital properties and host-star characteristics. This will include hot Jupiters to warm Super-Earths, orbiting M5 to F0 stars.

It will employ a 0.7 m x 1.1 m off-axis three mirror telescope, feeding four photometric channels in the VNIR range (0.5-2 um) and an IR spectrometer covering 2-8 um (R~100-30).

This paper describes critical science and mission requirements, and reports on the results of the Concurrent Design Facility (CDF) study that was conducted in June / July 2015, providing a description of the resulting spacecraft design, including critical subsystems such as AOCS and thermal/cryogenics.

9904-63, Session 16

The science of ARIEL (Atmospheric Remote-sensing Infrared Exoplanet Large-survey)

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ARIEL is a European mission being planned to answer fundamental questions about how planetary systems form and evolve. ARIEL will investigate the atmospheres of several hundreds planets orbiting distant stars. It is one of three candidate missions selected by the European Space Agency (ESA) for its next medium class science mission, due for launch in 2026. The ARIEL mission concept has been developed by a consortium of more than 50 institutes from 12 countries, including UK, France, Italy, Germany, the Netherlands, Poland, Spain, Belgium, Austria, Denmark, Ireland, Portugal.

During its 3.5-year mission, ARIEL will observe over 500 exoplanets ranging from Jupiter- and Neptune-size down to super-Earth and Earth-size in a wide variety of environments. The main focus of the mission will be on exotic, hot planets in orbits very close to their star. Hot exoplanets represent a natural laboratory in which to study the chemistry and formation of exoplanets. In cooler planets, different gases separate out through condensation and sinking into distinct cloud layers. The scorching heat experienced by hot exoplanets overrides these processes and keeps most molecular species circulating throughout the atmosphere.

ARIEL will have a meter-class mirror to collect visible and infrared (2-8 micron) light from distant star systems. The analysis of ARIEL spectra and photometric data will allow to extract the chemical fingerprints of gases and condensates in the planets' atmospheres, including the elemental composition for the most favorable targets. It will also enable the study of thermal and scattering properties of the atmosphere as the planet orbit around the star.

ARIEL will be placed in orbit around the Lagrange Point L2 to maximise the thermal stability and field of regard, and therefore its options for observing exoplanets discovered previously by other missions.

This paper outlines the science objectives and goals for the mission, and discusses how these are translated into detailed observational and performance requirements for the mission. The data processing and calibration methodologies planned for use are also discussed.

9904-64, Session 17

Lyot coronagraph design study for large, segmented space telescope apertures

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Recent efforts combining the optimization techniques of apodized pupil Lyot coronagraphs and shaped pupils have demonstrated the viability of a purely binary-transmission mask architecture for extremely high contrast (1E-10) exoplanet imaging. Building on the existing proofs of concept, we present a new investigation into the performance of a Lyot coronagraph optimized for a large, segmented aperture UVOIR (ultraviolet-optical-infrared) space observatory. We carry out design trials for a series of realistic telescope aperture geometries having various configurations of primary mirror segments, secondary support struts, and central obscuration. At the baseline raw contrast (1E-10) required to image a terrestrial analog, we map the performance parameter space over throughput, inner working angle, bandwidth, and image search zone geometry. Engineering metrics are translated to scientific yield by modeling a survey of nearby stars with a range of rocky planet populations. From our study, we aim to identify the most favorable segmented telescope aperture morphologies for exoplanet imaging, and to gain insights on the performance limits of Lyot coronagraphy on NASA's next flagship UVOIR space telescope.

9904-65, Session 17

PIAACMC-based coronagraphy for segmented apertures

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Future large space telescopes with segmented primary mirrors will have the sensitivity to spectrally characterize Earth-like habitable planets around other stars. While high performance coronagraphs have traditionally been developed for contiguous apertures, we show that segmented apertures are also fundamentally suitable for high contrast imaging. We have developed coronagraph solutions based on Phase-Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC) concept for several segmented and centrally obscured apertures. The PIAACMC design combines loss-less pupil apodization, performed with aspheric optics, with a multi-zone reflective or transmissive focal plane mask. The zones of the focal plane mask are computer optimized to produce a deep broadband destructive interference within the exit pupil, and can be further optimized to maintain high contrast imaging capability for partially extended stars.

We find no significant difference between PIAACMC performance on segmented and non-segmented apertures: PIAACMC can offer in both cases IWA around 1 to 1.5 l/D, near full throughput and no signiciant loss of angular resolution. The contrast at small angular separation is fundamentally limited by stellar angular size (in unit of lambda/D). On a large aperture, PIAACMC's small inner working angle enables spectroscopic observations of nearby habitable exoplanets in the near-IR, allowing atmospheric molecular composition to be measured. Thanks the the small IWA, habitable zones can be observed around later-type stars than otherwise possible, and the coronagraph can access a large number of more distant targets. We also discuss requirements and approaches for sensing small cophasing errors using either starlight rejected by the coronagraph, or bright diffraction spikes in the coronagraphic image.

9904-66, Session 17

The segmented aperture interferometric nulling testbed (SAINT) I: overview and air-side system description

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Direct detection and characterization of exosolar planets is predicated on collecting area and angular resolution available with large telescopes, as well as the ability to suppress starlight relative to the planet at small angular separations using coronagraphic techniques. This work presents an overview of the Segmented Aperture Interferometric Nulling Testbed (SAINT), a project that will pair an actively-controlled macro-scale segmented mirror with the Visible Nulling Coronagraph (VNC). SAINT will incorporate the VNC's demonstrated wavefront sensing and control system to refine and quantify the end-to-end system performance for high-contrast starlight suppression. This pathfinder system will be used as a tool to study and refine approaches to mitigating instabilities and complex diffraction expected from future large segmented aperture telescopes. The SAINT source, collimator, and segmented mirror telescope are located on a large optical bench in air and this system is adapted from a previously demonstrated sparse aperture phased array demonstrator, the Fizeau Interferometry Testbed (FIT). These optics form one of two selectable branches of a relay, the other being a bypass that delivers a circular aperture with Gaussian intensity profile. The relay incorporates a fast steering mirror (FSM) and vacuum window port into the Vacuum Nuller Testbed (VNT), a chamber that resides on the same optical bench. Inside the VNT chamber the VNC may operate at atmospheric pressure, at reduced pressure similar to a stratospheric balloon environment, or at high vacuum to emulate system operation in a space-like environment. An overview of the SAINT system and the project goals is provided along with a more detailed description of the air-side optics and a progress report on the fabrication and testing of these components.

9904-67, Session 17

A new deformable mirror architecture for coronagraphic instrumentation

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Coronagraphs are a promising solution for the next generation of exoplanet imaging instrumentation. While a coronagraph can have very good contrast and inner working angle performance, it is highly sensitive to optical aberrations. This necessitates a wavefront control system to correct aberrations within the telescope. The wavefront requirements and desired search area in a deformable mirror (DM) demand control of the electric field out to relatively high spatial frequencies. Conventional wisdom leads us to high stroke, high actuator density DMs that are capable of reaching these spatial frequencies on a single surface. Here we demonstrate a different architecture, where nearly every optical surface, powered or unpowered, is a controllable element. Rather than relying on a single, high-risk, controllable surface for the success of the entire instrument we propose using a series of lower actuator count deformable mirrors to achieve the same result by leveraging the conjugate planes that exist in a

coronagraphic instrument. To make such an instrument concept effective the imaging optics themselves must become precision deformable elements, akin to the deformable secondary mirrors at major telescope facilities. Such a DM does not exist commercially; all current DMs, while not necessarily incapable of carrying optical power, are manufactured with flat nominal surfaces. This simplifies control and manufacturing, but complicates their integration into an optical system because there is oftentimes a need to pack several into collimated space. Furthermore, high actuator count DMs cannot approximate low order shapes such as focus or tip-tilt without significant mid-spatial frequency residuals, which is not acceptable for a coronagraphic high-contrast imager. To address this we have been developing a new ferrofluid-based DM at Princeton. The mirror itself has the advantage of mechanically decoupling actuators from the optical surface, which allows for a continuously supported face sheet and an additional degree of freedom that affords precision control of the mirror's focal length. Regardless of the backing technology, the ability to integrate the wavefront control system into the nominal coronagraphic optical train simplifies packaging, reduces cost and complexity, and increases optical throughput of any coronagraphic instrument. This adds redundancy, increases controllability of the complex aberrations, and mitigates both cost and risk associated with a single high-actuator count device that the entire instrument performance relies on. For the ferrofluid DM, improvements in surface quality and the decoupling of actuator failures from surface shape makes it an ideal candidate for coronagraphic instrumentation. Here we simulate an optical system with a combination of controllable imaging optics both with and without a high order DM at the pupil. The relative performance of each configuration with regard to contrast, achievable bandwidth, and redundancy is discussed. The overall performance enhancements and risk associated with actuator failures on the assumed DM technology is also evaluated.

9904-68, Session 18

High contrast imaging in multi-star systems: technology development and first lab results

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Several starlight suppression systems have been demonstrated in the lab that can remove the leakage of light from a star down to almost 1e10 contrast, but only for single-star systems. Despite the ubiquity and importance of multi-star systems, they are typically excluded from mission target lists and multi-star imaging technology has not been strongly pursued.

We show preliminary laboratory results advancing the technology readiness of a method to directly image planets and disks in multi-star systems such as Alpha Centauri. This method works with almost any coronagraph (or external occulter with a DM) and requires little or no change to existing and mature hardware. Because of the ubiquity of multistar systems, this method potentially multiplies the science yield of many missions and concepts such as AFTA, Exo-C, Exo-S, EXCEDE, and potentially enables the detection of Earth-like planets (if they exist) around our nearest neighbor star, Alpha Centauri, with a small and cheap space telescope such as ACESat or Centaur+.

We identified two main challenges associated with double-star (or multi-star) systems and methods to solve them. The first challenge is that multi-star separation is typically beyond the outer working angle (spatial Nyquist frequency) of the deformable mirror. To address this, we are developing "Super-Nyquist Wavefront Control" (SNWC) where a mild grating or the DM itself effectively diffracts low-spatial frequency modes of the DM into higher frequencies. The second challenge is to separate and independently remove overlapping speckles from multiple stars. Speckles from each star are incoherent with respect to each other, and thus must be removed for each star independently. We solve this challenge by a new method we call "Multi-Star Wavefront Control" (MSWC), which involves partitioning the correction zone and DM modes in a way that completely decouples the wavefront control of the two stars and enables simultaneously solving for both.

We present our first lab results and model validation of: SNWC and MSWC. With SNWC, we demonstrate a high contrast speckle suppression beyond the spatial Nyquist limit of a 32x32 DM (i.e. beyond 16 l/D), and with MSWC, we demonstrate a high contrast dark zone in the presence of two stars. The demonstration is carried out at the Ames Coronagraph Experiment (ACE) testbed at NASA ARC in monochromatic as well as broadband light.

9904-69, Session 18

High-contrast imaging for complex aperture telescopes (HiCAT): testbed overview

Rémi Soummer, Mamadou N'Diaye, Laurent Pueyo, Marshall D. Perrin, Élodie Choquet, Lucie Leboulleux, Sylvain Egron, Johan Mazoyer, Space Telescope Science Institute (United States)

We present an overview of the HiCAT testbed, a project designed to integrate wavefront sensing and control with starlight suppression by coronagraphy for telescopes with complex aperture shapes (i.e. in the presence of central obstruction, support structures, or segmentation). The testbed design has the flexibility to enable studies with increasingly complex telescope aperture geometries starting with off-axis telescopes, then on-axis telescopes with central obstruction and support structures (e.g. WFIRST), up to on-axis segmented telescopes (e.g. including various concepts for a Large UV, Optical, IR telescope (LUVOIR), such as the High Definition Space Telescope (HDST)). The testbed alignment was completed in the summer of 2014, surpassing specifications with a total wavefront error of 13 nm rms over a 18 mm pupil. The testbed includes two Boston Micromachine MEMS deformable mirrors for wavefront control, and will also incorporate an Iris AO MEMS deformable mirror with 37 hexagonal segments to simulate a segmented aperture. In this communication we give an overview of the testbed design, hardware implementation, and first results. We also discuss the coronagraph designs selected for the testbed, based on our recent development of the hybrid Apodized Pupil Lyot Coronagraph (APLC) with shaped-pupil apodizations. These new APLC-type solutions using two-dimensional shaped-pupil apodizers are optimized to be quasi-insensitive to jitter and low-order aberrations, while improving the performance in terms of inner working angle, bandpass and contrast over a classical APLC.

9904-70, Session 18

Architectural considerations for starshade missions

Jonathan W. Arenberg, Tiffany M. Glassman, Steven Warwick, Northrop Grumman Aerospace Systems (United States)

We discuss the application of modern mission architecture design in support of starshade enabled exoplanet missions. Our goal is to collect into a unifying document the many considerations necessary for enabling such missions. We will examine over a decade of starshade design and how it has led to the development of mature exoplanet missions. Of particular interest to our discussion are missions that maximize the exoplanet yield and that are therefore able to provide a better characterization of the potentially habitable exoplanet candidates. For this reason we will focus on starshade design compatible with 8m or larger class space telescopes such as the ones proposed for the 2020s and beyond.

9904-71, Session 18

Starshade starlight-suppression performance with a deployable structure

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Starshades are an exoplanet direct-imaging architecture that uses a precisely-shaped screen to block the light from a star in order to achieve high-contrast imaging of exoplanets. The shape of the deployable starshade structure must precisely match the design shape in order to maintain the high level of starlight suppression. In this paper, we discuss analysis of error sources from the starshade structure including manufacturing, dynamics, and thermal distortion to show that the starshade can achieve the needed optical performance.

9904-72, Session 18

Suppression of astronomical sources using the McMath-Pierce Solar Telescope and starshades with flight-like optics

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The external starshade is a method for the direct detection and spectral characterization of terrestrial planets around other stars, a key goal identified in ASTRO2010. Tests of this approach have been and continue to be conducted in the lab and in the field (Samuele et al., 2010, Glassman et al., 2014) using non-collimated light sources with a spherical wavefront and at Fresnel numbers and resolution in excess of proposed flight missions. We extend the current approach to performing night-time observations of astronomical objects using small-scale (10-30cm) starshades and the McMath-Pierce Solar Telescope at Kitt Peak National Observatory. We place a starshade directly in the path of the beam from an astronomical object in front of the main heliostat. Using only flat mirrors, we then direct the light through the observatory path and reflect it off the West heliostat to an external telescope located approximately 270m away, for an effective baseline of 420m. This configuration allows us to make measurements of stars (flat wavefront sources) with a Fresnel number close to those expected in proposed full-scale space configurations. We present the results of our engineering runs conducted in 2015.

9904-73, Session 19

PLATO: a multiple telescope spacecraft for exo-planets hunting

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PLATO stands for PLAnetary Transits and Oscillation of stars and is a Medium sized mission selected as M3 by the European Space Agency as part of the Cosmic Vision program. The strategy behind is to scrutinize a large fraction of the sky collecting lightcurves of a large number of stars and detecting transits of exo-planets whose apparent orbit allow for the transit to be visible from the Earth. Furthermore, as the transit is basically able to provide the ratio of the size of the transiting planet to the host star, the latter is being characterized by asteroseismology, allowing to provide accurate masses, radii and hence density of a large sample of extra solar bodies.

In order to be able to then follow up from the ground via spectroscopy radial velocity measurements these candidates the search must be confined to rather bright stars. To comply with the statistical rate of the occurrence of such transits around these kind of stars one needs a telescope with a moderate aperture of the order of one meter but with a Field of View that is of the order of 50 degrees in diameter. This is achieved by splitting the optical aperture into a few dozens identical telescopes with partially overlapping Field of View to build up a mixed ensemble of differently covered area of the sky to comply with various classes of magnitude stars. The single telescopes are refractive optical systems with an internally located pupil defined by a CaF_2 lens, and comprising an aspheric front lens and a strong field flattener optical element close to the detectors mosaic. In order to continuously monitor for a few years with the aim to detect planetary transits similar to an hypothetical twin of the Earth, with the same revolution period, the spacecraft is going to be operated while orbiting around the L2 Lagrangian point of the Earth-Sun system so that the Earth disk is no longer a constraints potentially interfering with such a wide field continuous uninterrupted survey.

The environment, in terms of stray-light and radiation, is considered in the opto-mechanical design of the telescope, along with the need for a relatively uniform PSF size along such a huge Field of View. Details of the science aims, operations, and their implication in terms of telescope specifications and the choices adopted to cope with them are briefly given.

9904-74, Session 19

ESA CHEOPS mission: development status

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The ESA Science Programme Committee (SPC) selected CHEOPS in October 2012 as the first S-class mission (S1) within the Agency's Scientific Programme, targeting launch readiness by the end of 2017. The CHEOPS mission is devoted to the first-step characterisation of known exoplanets orbiting bright stars, to be achieved through the precise measurement of exoplanet radii using the technique of transit photometry. It is envisaged

as a partnership between the ESA Science Programme and Switzerland, with a number of Member States delivering significant contributions to the space segment development and operations.

CHEOPS is considered as a test case for implementing ”small science missions” in ESA with the following requirements: science driven missions selected through an open Call for missions (bottom-up process); a mission implementation cycle, from the Call to launch, drastically shorter than for M and L missions; and cost-capped missions to ESA with possibly higher Member States involvement than for M or L missions.

The paper describes CHEOPS development status, focusing on the performed hardware manufacturing and test activities.

9904-75, Session 19

CHEOPS: status summary of the instrument development

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CHEOPS (CHaracterizing ExOPlanets Satellite) is the first ESA Small Mission as part of the ESA Cosmic Vision program 2015-2025. The mission was formally adopted in early February 2014 with a planned launch readiness end of 2017.

The mission lead is performed in a partnership between Switzerland, led by the University of Bern, and the European Space Agency with important contributions from Austria, Belgium, France, Germany, Hungary, Italy, Portugal, Spain, Sweden, and the United Kingdom.

The mission is dedicated to searching for exoplanetary transits by performing ultrahigh precision photometry on bright starts already known to host planets whose mass has been already estimated through ground based observations. The instrument is an optical Ritchey-Chretien telescope of 30 cm clear aperture using a single CCD detector. The optical system is designed to imagine a de-focused PSF onto the focal plane with very tight stability and straylight rejection requirements providing a FoV of 0.32 degreed full cone.

The system design is adapted to meet the top-level science requirements, which asks for a photometric precision of 20ppm, in 6 hours integration time, on transit measurements of G5 dwarf stars with V-band magnitudes in the range 6≤V≤9 mag. Additionally is asks for a photometric precision of 85 ppm in 3 hours integration time of Neptune-size planets transiting K-type dwarf stars with V-band magnitudes as faint as V=12 mag.

Given the high demanding schedule and cost constrains, the mission relies mostly on components with flight heritage for the platform as well as for the payload components. Although several new developments are integrated into the design as for example the telescope structure and the very low noise, high stability CCD front end electronics.

The instrument and mission are going through critical design review in fall 2015 / spring 2016. This paper describes the current instrument and mission design with a focus on the instrument. It outlines the technical challenges and selected design implementation. Based on the current status, the instrument noise budget is presented including the current best estimate for instrument performance.

The current instrument design meets the science requirements and mass and power margins are adequate for the current development status.

9904-76, Session 19

The Transiting Exoplanet Survey Satellite (TESS): discovering exoplanets in the solar neighborhood

George R. Ricker, Massachusetts Institute of Technology (United States)

The Transiting Exoplanet Survey Satellite (TESS) will discover thousands of exoplanets in orbit around the brightest stars in the sky. In its two-year prime survey mission, TESS will monitor more than 200,000 bright stars in the solar neighborhood for temporary drops in brightness caused by planetary transits. This first-ever spaceborne all-sky transit survey will identify planets ranging from Earth-sized to gas giants, around a wide range of stellar types and orbital distances.

TESS stars will typically be 30-100 times brighter than those surveyed by the Kepler satellite; thus, TESS planets will be far easier to characterize with follow-up observations. For the first time it will be possible to study the masses, sizes, densities, orbits, and atmospheres of a large cohort of small planets, including a sample of rocky worlds in the habitable zones of their host stars.

An additional data product from the TESS mission will be full frame images (FFI) with a cadence of 30 minutes. These FFI will provide precise photometric information for every object within the 2300 square degree instantaneous field of view of the TESS cameras. These objects will include more than 1 million stars and bright galaxies observed during sessions of several weeks. In total, more than 30 million objects brighter than magnitude I=16 will be precisely photometered during the two-year prime mission. In principle, the lunar-resonant TESS orbit could provide opportunities for an extended mission lasting more than a decade, with data rates in excess of 100 Mbits/s.

An extended survey by TESS of regions surrounding the North and South Ecliptic Poles will provide prime exoplanet targets for characterization with the James Webb Space Telescope (JWST), as well as other large ground-based and space-based telescopes of the future.

TESS will issue data releases every 4 months, inviting immediate community-wide efforts to study the new planets, as well as commensal survey candidates from the FFI. A NASA Guest Investigator program is planned for TESS. The TESS legacy will be a catalog of the nearest and brightest main-sequence stars hosting transiting exoplanets, which should endure as the most favorable targets for detailed future investigations.

TESS is targeted for launch in 2017 as a NASA Astrophysics Explorer mission.

9904-77, Session 19

The TESS camera: modeling and measurements with deep depletion devices

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The Transiting Exoplanet Survey Satellite is a NASA Explorer-class mission to discover planets around nearby stars, with a special focus on Earth-like planets with potential for follow up characterization. The system is to be launched in 2017. The all-sky survey requires a suite of

four wide field-of-view cameras with sensitivity across a broad spectrum. Deep depletion CCDs with a silicon layer of 100 ?m thickness provide enhanced performance in the red wavelengths for sensitivity to cooler stars. The performance of the camera is critical for the mission objectives, with both the optical system and the CCD detectors contributing to the realized image quality. Expectations for image quality are studied using a combination of optical ray tracing in Zemax and simulations in Matlab to account for the interaction of the incoming photons with the 100 ?m silicon layer. The simulations include a probabilistic model to determine the depth of travel in the silicon before the photons are converted to photo-electrons, and a Monte Carlo approach to charge diffusion based on the remaining depth of travel of the photo-electron. An engineering unit camera including deep depletion CCDs was built and tested for optical performance across the full set of wavelengths and field angles. In this paper we describe the performance simulations and the corresponding measurements taken with the engineering unit camera, and discuss where the models agree well in predicted trends and where there are differences compared to observations.

9904-78, Session 20

Gaia basic angle, straylight, and focus

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The ESA Gaia mission is creating an all-sky astrometric survey with microarcsecond accuracy. Some payload components had stability requirements at the picometre and microkelvin levels. However, the large basic angle periodic variations found during commissioning suggest the real fluctuations are closer to the nanometre and sub-millikelvin scales. In addition, the straylight from the Sun and astronomical sources is much higher than expected. Finally, the telescope focus has not remained fixed, but evolved during the mission. These three effects are a challenge for mission operations, which had to adapt to the real conditions, and data analysis, which tries to fulfil the original requirements under substantially more unstable conditions.

A joint ESA-industry working group was created to study the straylight and basic angle variations. During more than a year, they first addressed the origin of the solar straylight and then concentrated in the basic angle. The Basic Angle Monitoring (BAM) signal and house-keeping data were analysed, both during nominal operations and spacecraft events, such as safe modes and special activities. Ad-hoc tests were carried out, introducing perturbations before one decontamination campaign. A map summarising all possible origins was created and explored. Previous finite element models were improved to provide full spacecraft thermo-elastic-optical simulations. Several levels of complexity were increasingly added to key structures to study the validity of the simulations. Sensitivity analyses were carried out including most components in the service and payload modules. The worst offenders and possible thermo- and thermo-elastic perturbation transmission mechanisms were identified.

In parallel, the scientists characterised the BAM signal in the Fourier space, obtained global astrometry solutions and independently fitted the basic angle variations using stellar measurements. The agreement between the BAM and astrometric data is remarkable at first order, demonstrating the existence of milliarcsecond payload oscillations and discontinuities due to thermal relaxation. Subtle effects, such as tens of microarcsecond variations correlated to the sky stellar density were subsequently detected. The connection between the basic angle, number of stars, laser frequency stability and on-board computer temperatures has been discussed. The potential use of house-keeping measurements to improve the data reduction has been studied. The variable solar radiation input due to the Gaia orbit and spacecraft aging has been addressed.

Contrary to pre-launch expectations, the image quality has been continuously evolving since the operations started. Monitoring tools are in place to trace it, and occasional actuations have been carried out to bring the telescopes back to focus using the secondary mirror actuators and wavefront sensors. A stable focus was an assumption for the PSF calibration, which needs to go down to the Poisson noise limit to account for many effects such as chromaticity, focal plane dependence and charge transfer inefficiency. Fortunately, the overall trend is of increased stability as the mission evolves.

In this talk, a status review of these three issued will be provided, with a focus on the mitigation schemes and the lessons learned for future space missions where extreme stability is a key requirement.

9904-79, Session 20

Enabling science with Gaia observations of naked-eye stars

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ESA's Gaia mission is performing an all-sky survey of stellar objects, collecting astrometric, photometric, and spectroscopic data. It was designed to observe every star in the magnitude range G = (6.0 - 20.0]. In our previous contribution that presented results obtained during in-orbit commissioning (Proc. SPIE. 9143), we demonstrated how the bright limit can be overcome to enable Gaia observations of naked-eye stars with magnitudes G < 6, thereby completing the astrometric survey at the bright end.

Here we update on the progress of very bright star observations during the nominal mission, which began in July 2014. We present the status after more than one year of data has been obtained, which allows us to produce preliminary statistics and performance metrics for very bright stars. We discuss the data products that are generated for G<6 stars and review the expected astrometric, photometric, and spectroscopic measurements that can be made with those data. Since naked-eye stars were not part of the nominal Gaia mission goals, this fulfills the important task to inform the astronomical community on the potential content of future Gaia data releases for those stars. Eventually, the work presented here will enable the scientific exploitation of these “unexpected” Gaia observations.

Gaia does not have an input catalogue, instead its observation strategy relies on real-time detection of stellar objects as they pass in the focal plane of the spinning spacecraft. Detection, confirmation, and observation of an object is accomplished by on-board computers. The optimisation of those computers' parameter configuration allowed us to extend the autonomous bright limit to G~3. We confirm this preliminary result

obtained during commissioning with new data obtained during the nominal mission.

The adopted solution to obtain astrometric data for the 230 stars with G<3 is to force data acquisition and recording with one class of Gaia CCDs called the Sky-Mapper. We describe the procedures that make this possible in operation, which include the prediction of focal plane transits for these stars, the dedicated commanding of the payload, and the data retrieval and ingestion in the operational database. Because these data are non-nominal, they are not treated by the Gaia pipeline. We will describe the status of an independent prototype data analysis scheme to analyse the Sky-Mapper images and extract the stellar photocentres.

We will also present of a technique named virtual object synchronization, which relies on extremely precise (a few pixels in the focal plane) predictions of stellar focal plane transits. We will show results of successful tests, where we secured astrometric, photometric, and spectroscopic data for extremely bright stars that otherwise would have been lost. We present a cost-benefit estimation of this mode and the prospects for implementation in the nominal mission.

Finally, we will outline how the presented techniques could further enhance the Gaia mission. For instance, Sky-Mapper images of Baade's window and Omega Cen are already being acquired regularly, because they promise to improve Gaia's results in these extremely dense regions of the sky. Other applications are presently under study.

9904-80, Session 20

Microarcsecond astrometric observatory THEIA : from dark matter to compact objects and nearby earths

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Theia is a logical successor to Gaia, as a focused, very high precision astrometry mission which addresses two key science objectives of the ESA Cosmic Vision program: the nature of dark matter and the search for habitable planets, and addresses a number of other science cases strongly synergistic with ongoing/planned missions, such as the nature of compact objects, motions of stars in young stellar clusters, follow-up of Gaia objects of interest), Theia's "point and stare" operational mode will enable us to answer some of the most profound questions that the results of the Gaia's survey will ask. Extremely-high-precision astrometry at 1-?as level can only be reached from space. The Theia spacecraft which will carry a 0.8m telescope is foreseen to operate at L2 for 3,5 years. The preliminary Theia mission assessment allowed us to identify a safe and robust mission architecture that demonstrates the mission feasibility within the Soyuz ST launch envelope and a M-class mission cost cap. We will present these features of the mission that has been submitted at the last ESA M4 call.

9904-81, Session 21

A joint infrared space observatory: SPICA revised and upgraded

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In the study of the various processes that govern formation evolution of planets, stars and galaxies over cosmic time the far-infrared is a truly unique wavelength domain; a major fraction of the starlight in the universe is processed through dust and gas and subsequently reemitted there - thus especially the infrared provides measurements to directly assess the physical state and energy balance of cool matter. Earlier (far) infrared space missions, although very successful, were hampered by either having a warm(ish) or a small(ish) size telescope, limiting the practically achievable sensitivity. The next step in far-infrared research can be made only with a mission with a large cold telescope, like the SPace Infrared telescope for Cosmology and Astrophysics (SPICA). This paper describes the revised mission configuration that is proposed for launch in the late 2020ies.

Over time the SPICA mission has evolved significantly from its original incarnation as proposed by the Japanese space agency JAXA. Currently SPICA is envisaged as a joint European-Japanese project to be implemented for launch and operations at the end of the next decade. Following a joint ESA-JAXA study into the technical and programmatic feasibility of possible mission configurations a new architecture has been chosen for the satellite. In this new architecture, derived from the ESA PLANCK mission, the optical axis of the 2.5 meter diameter cold telescope is perpendicular to the axis of the spacecraft. In this new concept 'V-grooves' to provide passive cooling as were used on PLANCK are be mounted between the telescope assembly and the satellite service module, resulting in an overall more effective cryogenic system. The solar cells to provide power are mounted on the bottom side of the service module, which is always oriented towards the sun.

With the redesign of the mission also the science payload has been updated. The mission will provide extremely sensitive – of order 5x10-20 W/m2 (5?/1hr) – spectroscopic capabilities from 17 through 230 ?m at resolutions ranging from R 50 through 3000. A high resolution R~30.000 capability is provided for the 12-18 ?m wavelength range. Imaging capabilities are provided for efficient broad band mapping in the 17-35 ?m domain, and spectroscopic imaging for small fields in the 35-230 ?m range. The spectroscopic sensitivity of the instrument suite will typically provide two orders of magnitude improvement over what has been attained to date corresponding to a truly enormous increase in observing speed. Such an exceptional leap in performance is bound to produce many scientific advances. Some of these are predictable today and form the core science case for SPICA and drive its design; but others are impossible to predict, and there will undoubtedly be much discovery science with SPICA.

9904-82, Session 21

New cryogenic system of the next-generation infrared astronomy mission SPICA

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We present the new design of the cryogenic system of the next-generation infrared astronomy mission SPICA under the new framework. The new design is based on the ESA-JAXA CDF study on the Next Generation Cryogenic InfraRed Telescope (NG-CryoIRTel, CDF-152(A)) with a 2 m telescope, and we modified the CDF design to accommodate the 2.5 m telescope to meet the science requirements of SPICA. The basic design concept of the SPICA cryogenic system is to cool the Science Instrument Assembly (SIA, which is the combination of the telescope and focal-plane instruments) below 8K by the combination of the radiative cooling system and mechanical cryocoolers without any cryogen. For effective radiative cooling, a series of thermal shields (V-Grooves), similar to those of the Planck mission, are adopted to reduce the heat flow from the ambient-temperature Service Module to towards SIA. Additional shield, telescope shield, which is actively cooled down to 25 K by the double-stage Stirling coolers, is placed between the V-Grooves and the telescope baffle. Some of the main structures to support SIA is to be thermally detached in orbit to reduce the heat load to SIA. Two sets of cryocoolers (4.5 K and 1.7 K Joule-Thomson coolers with Stirling coolers) are used to cool the telescope below 8 K and the focal-plane instruments and detectors to various temperature stages below 6 K. The required cooling power for cryocoolers is compatible with the cooling capability of a series of cryocoolers developed by JAXA. One of the focal-plane instruments, SPICA Far-Infrared Instrument (SAFARI) has additional sub-K cooling system. The current design enables the cryogenic observing system of SPICA without any cryogen.

9904-83, Session 21

SPICA mid-infrared instrument (SMI): technical concepts and scientific capabilities

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SMI (SPICA Mid-infrared Instrument) is one of the two focal-plane scientific instruments planned for new SPICA. SMI covers the wavelength range of 12 to 36 microns, using the following three spectroscopic channels with unprecedentedly high sensitivities: low-resolution spectroscopy (LRS; R=50-120, 17-36 microns), mid-resolution spectroscopy (MRS: R=1300-2300, 18-36 microns), and high-resolution spectroscopy (HRS: R=30000, 12-18 microns).

More specifically, SMI-LRS is a multi-slit prism spectrometer of a wide field-of-view with 4 long slits of 10' in length. SMI-LRS is operated in combination with a 10' x 10' slit viewer to determine the positions of the slits on the sky. SMI-LRS has a very high continuum sensitivity (~30 microJy in 1 hr, 5 sigma). SMI-MRS is a grating spectrometer with a long slit of 1' in length, very high line sensitivity (~3 x 10-20 W/m2 in 1 hr, 5 sigma). SMI-HRS is an immersion grating spectrometer with very high line sensitivity (~2 x 10-20 W/m2 in 1 hr, 5 sigma). SMI-MRS and HRS are operated in combination with a beam-steering mirror at their common fore-optics to perform spectral mapping of relatively small areas. On the other hand, the design of SMI-LRS with the slit viewer is based on wide-area surveys in a telescope step-scan mode to produce a spectral map of ~10' x 10' area as a minimum field unit.

Scientifically, LRS enables us to study spectral bands due to dust grains such as polycyclic aromatic hydrocarbons (PAHs) from an extremely large number of star-forming galaxies at redshifts from 0.5 up to 7, and silicate grains from many planet-forming debris disks of mid-IR luminosities down to levels close to that of our solar system. As by-products, the SMI-LRS spectral surveys provide broad-band images with the slit viewer (R = 5, the central wavelength of 34 microns), which are also important as legacy datasets since the 30-40 micron region is an unexplored gap between the Spitzer 24 micron and the Herschel 70 micron surveys. Another important feature is that HRS enables us to perform velocity-resolved studies of fundamental molecular gases (H2, H2O, CO) such as those in the innermost regions of protoplanetary disks and in the energetic outflow of active galactic nuclei. Complementarily to these specific functions of LRS and HRS, MRS provides more versatile spectroscopic functions, for example, for follow-up spectroscopy of targets detected by SMI-LRS to study dust bands and gas lines in more detail.

In this presentation, we will show the technical concepts and current specifications as well as the expected scientific capabilities of SMI.

9904-84, Session 21

Achieving extreme sensitivity in the FAR-IR: the SAFARI grating spectrometer for SPICA

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The far-infrared spectrograph SAFARI, on the joint European-Japanese space telescope SPICA (the next step after ESA's Herschel mission), will provide the most sensitive view ever of the cool, obscured universe. By cooling the SPICA telescope to below 8 K its thermal emission is decreased to such low levels that the latest generation of ultra-sensitive Transition Edge Sensor (TES) detectors can be utilized to their full potential. With this combination of low background and extreme detector sensitivity SPICA will be able to look far deeper into space than was possible with any of its predecessors. SPICA/SAFARI is the only facility that will fill the gap in the wavelength domain between the other great observatories, and is as sensitive as both the James Webb Space telescope and the ALMA radio observatory – only with SPICA/SAFARI we will complete the view on the star-formation history of our universe.

The current baseline SAFARI design uses a beam steering mirror (BSM) that forwards the incoming signal to the dispersing and detection optics. The BSM is used to select sky or calibration signals and forward that to a nominal R~300 (low) resolution optics chain or to a R~3000 (high) resolution optics chain. The low resolution is obtained by dispersion through a diffraction grating illuminating a line of TES detectors. For the high resolution mode the signal is first pre-dispersed using Fabry-Pérot etalons before entering the grating, alternative options to achieve this pre-dispersion are being investigated. The full 35-230 ?m wavelength range is split in to several different bands, each with its own grating and TES detectors. The baseline design has for each of the bands three separate spatial pixels, to provide background reference measurements, but also to provide some imaging capability.

An earlier design for the SAFARI instrument was based on a Mach-Zehnder Fourier Transform Spectrometer. As in an FTS the detectors continuously are exposed to the full broad band signal, the sensitivity of such an architecture is fundamentally limited by photon noise, which in practice implied a sensitivity limit of around 2 x 10-19 W/m2 (5?, 1hr). With SPICA's cold, 2.5 meter telescope and the baseline TES NEP of 2x10-19 W/√Hz, for the new grating based SAFARI the sensitivity of the R~300

mode will be about 5 x 10-20 W/m2 (5?, 1hr). With the current design further improvements in TES performance will directly lead to even higher instrument sensitivity – today's state of the art TES performance is already close to 1x10-19 W/√Hz! With this high sensitivity astronomers will e.g. be able to detect the [OIV] line in relatively average galaxies out to a redshift z~3. Thus the evolution of galaxies can be followed through their most active periods in cosmic time from about 10 billion years ago to what they look like today. Additionally we will be able to observe dust features from even earlier epochs, out to redshifts of z~7-8, thus providing insight into dust formation in the very early phases of the universe.

9904-85, Session 21

The far infrared spectroscopic explorer (FIRSPEX) : probing the life cycle of the ISM in the universe

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The complex processes that initiate cloud collapse enabling the onset of star formation and subsequent stellar evolution leave their imprint on the Interstellar Medium (ISM) of our Galaxy and that of external galaxies. By studying the phase structure of the ISM we can begin to unravel the processes that control the heating and cooling of the clouds that eventually regulate star formation. FIR/submm spectroscopy is essential in probing these processes since this regime contains important cooling lines of the different phases of the ISM.

The Far InfraRed Spectroscopic EXplorer (FIRSPEX) is a novel concept for an astrophysics satellite mission that will revolutionise our understanding of the life cycle of the ISM starting from our own Galaxy out to distant galaxies. To achieve this goal we aim to obtain fully sampled velocity-resolved observations of carefully chosen key far infrared lines (e.g. CII, NII, OI) each probing a different component of the ISM. The spectral range selected contains important molecular, atomic and ionic species that cannot be observed from the ground. The FIRSPEX payload consists of a number of heterodyne detection bands targeting key molecular and atomic transitions in the terahertz (THz) and Supra-Terahertz (>1 THz) frequency range. The FIRSPEX bands under consideration are: [NII] 122 microns (2.5 THz), OH 119 microns (2.45 THz), [CII] 158 microns (1.9 THz), [NII] 205 microns (1.46 THz), [CI] 370 microns (0.89 THz), CO(6-5) 433 microns (0.69 THz). The choice of the channels has been motivated by the need to study the atomic, ionized and molecular phases of the ISM both in our own Galaxy but also in external galaxies.

The mission uses a heterodyne payload and a ~1.2m primary antenna to scan the entire sky in a number of discreet spectroscopic channels from L2. While superconducting receivers operating at ~4K temperature represent the most sensitive technology for heterodyne systems in space the current FIRSPEX baseline concept relies on the use of semiconductor Schottky diode mixers as the primary detection element in each of the high spectral resolution heterodyne receivers. Each receiver will operate within a well-defined spectral range corresponding to the key species discussed above. A wide-band digitizing spectrometer will provide an instantaneous bandwidth ~10 GHz with high spectral resolution. Adequate local oscillator (LO) power, a crucial element of the heterodyne mixing process, will be provided by sub-harmonic mixer using harmonic frequency up-conversion. It is also possible to use quantum cascade laser (QCL) technology with the Schottky mixers configured in a balanced fundamental format (for the >1.5 THz receivers). The mixers and QCL LOs can operate at a 100 K, with cooling provided by previously space-qualified and demonstrated Stirling cycle mechanical cooler. FIRSPEX will perform an `unbiased' all-sky spectroscopic survey of the Galaxy and of external galaxies opening a completely new window of scientific discoveries.

9904-86, Session 21

The Space High Angular Resolution Probe for the Infrared (SHARP-IR)

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The Space High Angular Resolution Probe for the Infrared (SHARP-IR) is a new mission currently under study. As part of the preparation for the Decadal Survey, NASA is currently undertaking studies of four major missions, but interest has also been shown in determining if there are feasible sub-$1B missions that could provide significant scientific return. SHARP-IR is being designed as one such potential probe. In this talk, we will discuss some of the potential scientific questions that could be addressed with the mission, the current design, and the path forward to concept maturation.

Conference 9905: Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray

Sunday - Friday 26–1 July 2016

Part of Proceedings of SPIE Vol. 9905 Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray

9905-1, Session 1

SMILE: a joint ESA-CAS mission to investigate the interaction between the solar wind and Earth's magnetosphere

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The Solar wind Magnetosphere Ionosphere Link Explorer (SMILE) is a collaborative science mission between ESA and the Chinese Academy of Science (CAS). SMILE is a novel self-standing mission to observe the coupling of solar wind and Earth's magnetosphere via simultaneous in-situ solar wind, magnetosheath plasma and magnetic field measurements, X-Ray images of the solar wind - magnetosphere interaction zones, and UV images of global auroral distributions. The SMILE mission proposal was submitted by a consortium of European, Chinese and Canadian scientists following a joint call for mission by ESA and CAS. It was formally selected by ESA's Science Programme Committee (SPC) as an element of the ESA Science Program in November 2015, with the goal of a launch in the 2021 - 2022 time frame.

In order to achieve its scientific objectives, the SMILE payload will comprise four instruments: the Soft X-ray Imager (SXI), which will spectrally map the Earth's magnetopause, magnetosheath and magnetospheric cusps; the UltraViolet Imager (UVI), dedicated to imaging the auroral regions; the Light Ion Analyser (LIA) and the MAGnetometer (MAG), which will establish the solar wind properties simultaneously with the imaging instruments. We will report on the status of the mission and payload developments and the findings of a design study carried out at the concurrent design facility (CDF) of ESTEC and the National Space Science Center (NSSC,CAS) in October/November 2015.

9905-2, Session 1

The solar ultraviolet imaging telescope onboard Aditya-L1

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The Solar Ultraviolet Imaging Telescope (SUIT) is an instrument onboard the Aditya-L1 spacecraft, the first dedicated solar mission of Indian Space Research Organization (ISRO), which will be put in an halo orbit at Sun-Earth Langrage point (L1). SUIT uses an off-axis Ritchey–Chrétien configuration telescope with a combination of 11 narrow and broad bandpass filters that will take images of the Sun in 200-400 nm. It will provide near simultaneous observations of lower and middle layers solar atmosphere, namely Photosphere, Chromosphere and lower transition region. These observations will help improving our understanding of coupling and dynamics of various layers of solar atmosphere, mechanisms responsible for stability, dynamics and eruption of solar prominences and CMEs, and possible causes for solar variability in the NUV region.

SUIT employs a 4Kx 4K UV enhanced CCD detector with a 12 micron pixel size to provide a resolution of 0.7 arcsecond/pixel with a ~48 sq. arcminutes field of view. The 11 filters consisting of 8 narrow and 3 board bandpass filters, in combination with 4 clear and neutral density filters will be employed via two independent filter wheel mechanisms. It will provide Region of Interest images in all 8 narrow band filters with a cadence of 30 seconds and full frame images in all 11 filters with a cadence of 30 minutes. The out of band solar flux i.e., the visible and IR region is rejected by an entrance aperture filter that also cuts the excessive flux in the UV region.

SUIT will autonomously operate based on preprogrammed operational sequences that will take Full frame and Region of Interest Images (500 sq. arcseconds) in different filters. During its science operations SUIT will operate in two modes: Normal and Flare mode, with an autonomous decision making capability to switch from Normal to Flare mode (and back) based on flare detection trigger from another payload onboard Aditya-L1. The massive volume of data generated from SUIT will be compressed and stored on-board and will be down linked to ground-station when the spacecraft is visible. This onboard autonomy will enable SUIT to provide 24x7 coverage of the sun even when the spacecraft is not visible from the ground-station. SUIT observations in combination with other payloads onboard Aditya-L1, E-VELC, SoLEX and HEL1OS, will provide a comprehensive perspective of different layers of solar atmosphere.

9905-3, Session 1

World Space Observatory Ultraviolet mission: status 2016

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The space mission World Space Observatory - Ultraviolet (WSO-UV) is grown out the needs of the astronomical community to have access to the Ultraviolet (UV) range 115-320 nm of the spectrum in post-HST epoch. WSO-UV consists of a UV telescope of 1.7 m primary mirror diameter and a set of UV low and high spectral resolution spectrographs and UV-optical imagers.The project is in an advanced phase of creation. The current state of art of the mission will be described. The materials on selection of initial parameters of the Spacecraft, Payload, Operational orbit and Ground Segment will be presented.

9905-4, Session 1

Galaxy evolution spectroscopic explorer (GESE): a companion to high-energy observatories

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The history of the universe can be described as the continuous conversion of gas into stars. However, it is clear that star formation is impeded by “feedback” from newly formed massive stars themselves, by stellar-mass black holes and AGN’s, and by the influence of dark energy in counteracting the long-range effects of gravity. Space telescopes sensitive to far-UV radiation from massive stars, supernova explosions, and AGN’s give information that is complementary to that gained by x-ray telescopes. Using a UV mission concept called Galaxy Evolution Spectroscopic Explorer (GESE) as an example, we describe the synergy between UV and high-energy telescopes.

9905-5, Session 1

CHISL: combined high-resolution and imaging spectrograph for the LUVOIR surveyor

Kevin C. France, Brian T. Fleming, Keri Hoadley, Univ. of Colorado Boulder (United States)

NASA is currently carrying out science and technical studies to identify its next astronomy flagship mission to begin development in the 2020s. It has become clear that a Large Ultraviolet/Optical/IR (LUVOIR) Surveyor mission (dprimary ≈ 12 m, ?? ≈ 912 Å – 2 μm spectroscopic bandpass) can carry out the largest number of NASA’s exoplanet and astrophysics science goals over the coming decades. The science grasp of a LUVOIR Surveyor is broad, ranging from the direct detection of potential biomarkers on rocky planets to the flow of matter into and out of galaxies and the history of star-formation across cosmic time. There are significant technical challenges for many aspects for the LUVOIR Surveyor concept, including component level technology readiness maturation and science instrument concepts for a broadly capable ultraviolet spectrograph. We present the scientific motivation for, and a preliminary design of, a multiplexed ultraviolet spectrograph to support both the exoplanet and astrophysics goals of the LUVOIR Surveyor mission concept, the Combined High-resolution and Imaging Spectrograph for the LUVOIR Surveyor (CHISL). CHISL includes a high-resolution (R > 120,000) point-source spectroscopy channel and a medium resolution (R > 10,000) imaging spectroscopy channel for topics as broad as characterizing the composition and structure of planet-forming disks to the feedback of matter between galaxies and the intergalactic medium. We present the CHISL concept, potential science enhancing technical additions (e.g., an aperture system supporting multi-object spectroscopy), and identify the primary technological hurdles. Technical challenges include high-efficiency ultraviolet coatings and high-quantum efficiency, large-format, photon counting detectors. We are actively engaged in laboratory and flight characterization efforts for all of these enabling technologies as components on sounding rocket payloads currently under development at the University of Colorado. We describe two payloads that are designed to be pathfinder instruments for the high-resolution (CHESS) and imaging spectroscopy (SISTINE) arms of CHISL. We are carrying out this instrument design, characterization, and flight-testing today to support the new start of a LUVOIR Surveyor mission in the next decade.

9905-6, Session 2

Optical design and optical properties of a VUV spectrographic imager for ICON mission

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The ICON mission is led by the University of California-Berkeley (Space Sciences Laboratory). In the frame of this mission the Space Center of Liege was involved into the optical design optimization and related analysis.

The ICON mission (NASA) will explore the boundary between Earth and space to understand the physical connection between our world and our space environment. Recent NASA missions have shown how dramatically variable the region of space near Earth is, where ionized plasma and neutral gas collide and react. This region, the ionosphere, has long been known to respond to space weather drivers from the sun, but in this century we have come to realize that the energy and momentum of our own low altitude atmosphere regularly affect the ionosphere with equal or greater magnitude. ICON will weigh the impacts of these two drivers as they exert change on our space environment.

During the day, photoelectrons colliding with atmospheric neutrals, N2 and O, produce emissions and by observing the limb brightness of the N2 Lyman-Birge-Hopfield (LBH) bands and of the OI 135.6 nm line, the density ratio of the neutral N2 and O atmospheric constituents can be retrieved. At night the recombination of O+ ions with ionospheric electrons also creates OI 135.6 nm emissions and the nighttime electron density can be estimated from the limb brightness of 135.6 nm. ICON FUV will measure the altitude distribution of the OI 135.6 nm and N2 LBH dayglow emissions at 157 nm and the altitude and spatial distribution of the OI 135.6 nm nightglow emissions. These quantities can then be used to determine dayside O and N2 densities and altitude profiles, and the nightside O+ densities in the F-region.

The ICON-FUV instrument is based upon the IMAGE Spectrographic Imager (SI) [Mende et al., 2000c]. Like this predecessor, ICON-FUV is a two-channel imager that uses a grating spectrometer for spectral discrimination. The two channels are required to provide the daytime profiles of two wavelengths characterizing the N2 and O species (centered at 157 nm and 135.6 nm respectively). This grating type of spectrographic imager minimizes contamination by out-of-band light leaks that are a typical problem for non-grating type FUV cameras.

In this paper the optical design and optimization process will be presented. The instrument is composed by two parts, a Czerny-Turner spectrograph selecting the science wavelengths. This spectrograph is then combined with two imagers respectively working in the two wavebands of interest. The challenge of this space instrument was to be designed for a very wide FOV (24° vertical by 18° horizontal).

The instrument has been optimized in two main steps including payload platform constrains. First the Czerny-Turner spectrograph has been designed to reduce as much as possible the astigmatism generated by the grating and to give the same spectral properties over the entire field of view, secondly the two imagers based on aspheric and off-axis mirrors have been designed.

Optical properties, instrument throughput, flat field evaluation and tolerance analysis will be presented.

9905-7, Session 2

Chromospheric LAyer SpectroPolarimeter (CLASP2)

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The solar chromosphere is a crucial interface region between the solar photosphere (6000 K) and the corona (more than 1 MK). Observations (e.g., with the Hinode and IRIS space telescopes) show very dynamic phenomena in the chromosphere (e.g., jets, waves, etc.), including clear hints of heating events. However, our quantitative knowledge on the magnetic field and on the dissipation of magnetic energy in the chromosphere-corona transition region is practically inexistent, since no space telescope has ever been developed to carry out spectropolarimetric measurements in the ultraviolet resonance lines that originate in the upper solar chromosphere and transition region. With this motivation in mind, the Chromospheric Lyman-Alpha SpectroPolarimeter (CLASP) was proposed, designed and launched on September 3rd, 2015, using a NASA sounding rocket. For the first time, CLASP successfully detected (with a polarization accuracy of 0.1 %) the linear polarization signals (Stokes Q and U) that scattering processes were predicted to produce in the hydrogen Lyman-alpha line (Lya; 121.567 nm). Via the Hanle effect, this unique data set may provide information about the magnetic structure and energetics in the upper solar chromosphere. The CLASP instrument was safely recovered without any damage and we have recently proposed to dedicate its second flight to observe the four Stokes profiles (intensity, linear and circular polarization) in the spectral region of the Mg II lines around 280 nm (Mg II k; 279.55 nm, and Mg II h; 280.27 nm), in order to exploit the Hanle effect in the linear polarization (Stokes Q and U) of the k line and the Zeeman effect in the circular polarization (Stokes V) of the k and h lines. This new project is called the "Chromospheric LAyer SpectroPolarimeter (CLASP2)". Essentially, for CLASP2 we will reuse, i.e., keep, the optical layout of the CLASP (Narukage et al., 2015). Nevertheless, because of the change in the wavelength target from 122 nm to 280 nm, the waveplate, grating and polarization analyzer will be re-fabricated and the narrow band filter coating on the primary mirror will be also re-coated. Additionally, we plan to develop and install a magnifying lens in front of the CCD camera for keeping the same wavelength sampling as in the CLASP. This modification will make CLASP2 suitable to detect the linear and circular polarizations signals across the Mg II lines with a 0.1 % accuracy and a wavelength sampling of 0.005 nm. The spectropolarimetric observations carried out by CLASP in Lya and by CLASP2 in Mg II h & k will be useful to constrain better the magnetic structure of the upper solar chromosphere, given the different magnetic sensitivities and formation heights of such resonance lines. Additionally, the data sets from CLASP and CLASP2 will help us decide the most suitable strategies for probing the outer solar atmosphere through spectropolarimetry from a future space telescope.

9905-8, Session 2

The miniature x-ray solar spectrometer (MinXSS) CubeSat instrument characterization techniques, instrument capabilities, and solar science objectives

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The Miniature X-ray Solar Spectrometer (MinXSS) is a 3U CubeSat launched in December 2015 to the International Space Station for deployment in early 2016. MinXSS will utilize a commercial off the shelf (COTS) X-ray spectrometer from Amptek to measure the solar irradiance from 0.5 – 30 keV with a nominal 0.15 keV FWHM spectral resolution at 5.9 keV and a LASP developed X-ray photometer with similar spectral sensitivity. MinXSS design and development has involved over 40 graduate students supervised by professors and professionals at the University of Colorado at Boulder.

The majority of previous solar X-ray measurements have been either at high spectral resolution with a narrow bandpass or spectrally integrating (broad band) photometers. MinXSS will conduct unique soft X-ray measurements of moderate spectral resolution over a relatively large energy range to study solar active region evolution, solar flares, and their effects on Earth's ionosphere. This paper focuses on the science instrument characterization involving radioactive X-ray sources and the National Institute for Standard and Technology (NIST) Synchrotron Ultraviolet Radiation Facility (SURF). Detector spectral response, spectral resolution, response linearity are discussed as well as future solar science objectives.

9905-9, Session 2

SISTINE: a pathfinder for far-UV imaging spectroscopy on future NASA astrophysics missions

Brian T. Fleming, Kevin C. France, James C. Green, Univ. of Colorado Boulder (United States); Oswald H. W. Siegmund, Sensor Sciences, LLC (United States); Manuel A. Quijada, NASA Goddard Space Flight Ctr. (United States); Robert Kane, Nicholas Nell, Univ. of Colorado Boulder (United States)

The University of Colorado ultraviolet sounding rocket group is finalizing the design of the Suborbital Imaging Spectrograph for Transition Region Irradiance from Nearby Exoplanet host stars (SISTINE); the first sub-arcsecond imaging, medium resolution spectrograph capable of simultaneous coverage of the entire 1000 – 1580 Angstrom bandpass. SISTINE is designed as a pathfinder instrument for maturing critical path technologies necessary for the LUVOIR surveyor. Utilizing a breakthrough advancement in broadband mirror coatings, SISTINE folds a large effective focal length into a sounding rocket envelope without a crippling loss of effective area. These enhanced lithium fluoride protected aluminum (eLiF)

coatings, developed at Goddard Space Flight Center, offer greater than 80% reflectivity from the far-ultraviolet through the near-infrared, and will be flight tested on SISTINE in preparation for implementation on future space observatories. When coupled with next-generation large-format borosilicate microchannel plate detectors developed at Sensor Sciences, SISTINE is capable of a resolving power of 10,000 over its entire band with a peak effective area of 170 cm2, representing a high throughput for an FUV instrument of > 10%. This system throughput is a factor of ~10 higher than the medium resolution far-ultraviolet imaging spectroscopy modes on HST-STIS. We present the design and an outline of the science goals of SISTINE, as well as a schedule of fabrication and calibration milestones necessary for completion of the instrument. The first flight of SISTINE is planned for 2018 to observe the energetic radiation environment of nearby low-mass exoplanet host stars.

9905-10, Session 3

Flight production of Caliste-SO: the hard x-ray spectrometers for solar orbiter/STIX instrument

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On board the Solar Orbiter mission to be flown in 2018, the Spectrometer Telescope Imaging X-rays will perform X-ray imaging spectroscopy of solar flares to study the physical properties of these eruptive events (plasma temperature, acceleration mechanisms) and the Sun-heliosphere connection (magnetic energy conversion and release). The imaging technique consists in a Fourier transform based on 32 X-ray collimators, each of them with a pair of grids and a spectrometer. Caliste-SO is the spectrometer unit designed for STIX. It is the hybridization of a 1 cm2 pixel CdTe sensor with a radiation hard low noise front-end ASIC called IDeF-X HD. With a 12 x 14 x 18 mm3 volume, a 5 g mass and a 20 mW total power, the resulting device integrates 12 high-resolution spectroscopic channels. The spectrometer is well adapted for X-ray detection from 4 keV (70 % efficiency, low-level threshold of the front-end electronics below 3 keV) to 150 keV (50 % efficiency, dynamic range of the front-end electronics up to 250 keV), allowing observations of both thermal and non-thermal emissions of the solar flares. Ninety-eight Caliste-SO units passed performance criteria (energy resolution) and quality criteria (crystal defects, metrology) to be mounted into a validation model of STIX. Energy resolution of most pixels is between 0.8 and 1 keV FWHM at 14 keV (measurements with 241Am source) when the detector is cooled down at -20°C and biased at -300V, for a peaking time of 2 μs. This performance can be achieved thanks to the hybridization process which limits the stray capacitance between the pixels and the ASIC channels to 2 pF. Even better spectral performance (< 0.7 keV) can be obtained at longer peaking times (programmable in the Caliste-SO ASIC) but that would be to the detriment of the timing performance. Photon count rate produced during solar flares can indeed vary from few photons/s/cm2 to millions of photons/s/cm2, according to the event class and evolving with time. The STIX instrument will be equipped with a removable X-ray attenuator in case of bright events but the count rate capability of Caliste-SO shall be of 20000 counts/s/cm2 at least while maintaining spectral capabilities. With 2 μs peaking time, the pile-up fraction stays below 1%. Caliste-SO qualification and further characterizations are on-going before mounting the first units on the STIX flight model in 2016.

9905-12, Session 3

Ultraviolet imaging detectors for the GOLD mission

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The GOLD mission is an ultraviolet Earth observing spectroscopy instrument that will be flown on a telecommunications satellite in geosynchronous orbit in 2017. GOLD has two identical spectrometer channels operating in the 130 nm to 170 nm UV bandpass regime and is designed to observe atmospheric UV emission from oxygen and nitrogen. The objective is to measure the composition and temperature of the thermosphere dynamically at a cadence of the order of about 30 minutes. We will describe the microchannel plate detectors with 2D imaging cross delay line readouts and electronics have been built for each of the spectrometer channels. The two detectors are "open face" with CsI as a photocathode deposited onto the top surface of the MCPs. Each detector is enclosed in a vacuum housing with a re-closable door. The detectors provide ~500 x 500 resolution elements and are photon counting. The detector electronics are based on amplification stages followed by a time to digital converter to convert anode delay times to X and Y positions. The electronics event dead-time is ~1 μs which allows event rates of up to 100 kHz to be processed with minimal losses. The background rates are as low as 0.15 events sec-1 cm-2, and the flat field fixed pattern noise is quite low (~5%) for this generation of microchannel plates. Quantum efficiencies have been optimized and are at the same level as detector on the HST COS instrument. Image resolution, counting rates and image linearity are principally determined by the electronics system. The constraints on available power and mass in concert with the science instrument performance drivers control the design choices for the electronics package. Data for each photon detection includes a 4k x 4k position and an event pulse amplitude. The latter is also used to reject high amplitude events due to charged particles that are expected to increase the background in geosynchronous orbit. Local event rates are greater than 10 events/pore/sec and are determined by the choice of low resistance microchannel plates. This accommodates bright spectral lines and stellar calibration observations. Thermal stability and long term performance stability of the detector system will be discussed. Electronics stimulation pulses are also injected into the electronics processing chain at all times. These provide useful diagnostics on the health of the detector and electronics. The overall construction, testing and calibration of the GOLD detectors will be detailed in this paper, along with a discussion of their impact on the mission.

9905-13, Session 3

The FOXSI solar hard x-ray rocket campaigns

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The Focusing Optics X-ray Solar Imager (FOXSI) sounding rocket experiment has successfully been flown twice for 6.5 minute observations of the Sun. The experiment's goals are to develop hard X-ray (HXR) focusing optics technology for solar astrophysical purposes, and to demonstrate the use of this technology by performing novel solar investigations. To achieve these goals, FOXSI relies on grazing-incidence focusing HXR optics produced at the NASA Marshall Space Flight Center and thin, fine-pitch semiconductor detectors (Si and CdTe) provided by the JAXA Institute of Space and Astronautical Science in Japan.

The FOXSI-1 rocket flew on 2012 November 2 and imaged a solar microflare, producing the first focused images of the Sun above 5 keV. FOXSI-2 flew on 2014 December 11 and produced images and spectra of multiple flares and active regions. Several upgrades were included for the second flight, such as the addition of smaller-diameter mirrors to extend the energy range to ~20 keV, the inclusion of two 60 um pitch CdTe sensors in addition to the original 75 um Si sensors, and a new optical solar aspect and alignment system. FOXSI data have been used to measure and constrain high-temperature plasma in active regions, and have placed limits on flaring activity in the quiet Sun, both important for understanding flare contributions to coronal heating.

All FOXSI observations to date have experienced an instrumental background due to ghost rays (single-bounce photons) from sources outside the field of view. While ghost-ray backgrounds are not unique to solar science, the frequent occurrence of bright sources distributed across the solar disk means that ghost rays pose a special challenge for solar observation. Ghost rays can be highly attenuated by the addition of a pre-collimator (baffle) to the entrance of the grazing incidence optics.

In this work we present an overview of the FOXSI rocket instrument, discuss requirements for a pre-collimator to attenuate ghost rays, and outline future plans for the project.

9905-134, Session 3

The faint intergalactic medium redshifted emission balloon: FIREBall-2 ready for flight

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The Faint Intergalactic Redshifted Emission Balloon (FIREBall-2) is a joint NASA/CNES collaboration that is preparing to launch in mid-summer 2016 from Palestine, TX. FIREBall-2 is a balloon-born UV multi-object spectrograph designed to detect faint emission from the circumgalactic medium (CGM) around low z galaxies. FIREBall-2 builds on the existing gondola and large optics of FIREBall-1, but has been extensively redesigned to improve performance by over an order of magnitude. To improve instrument throughput, a photon-counting delta-doped EMCCD has replaced the GALEX spare NUV micro channel plate. Custom red blocking coatings minimize out-of-band light and improve in-band transmission. FIREBall-2 will flight test these technology innovations in anticipation of the 2016 MIDEX AO. Here we discuss the final flight design, results from integration and testing in Marseille earlier in 2016, and the ongoing final preparations for flight. We also describe target fields and expected performance in flight.

9905-135, Session 3

Imaging the circumgalactic and intergalactic medium in the space ultraviolet

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We describe the scientific case and technical approach for an Explorer designed to image the Circumgalactic Medium (CGM) and Intergalactic Medium (IGM) in the space ultraviolet. Our science method builds on discoveries made with the Palomar Cosmic Web Imager (PCWI). We will perform an imaging survey to make a complete census of Lyman alpha emitters (LAE) at redshifts 0.01< z<1.5, a period of dramatic evolution in the LAE population. We will construct a reference sample that we will map and characterize using 2D imaging spectroscopy. We will perform a survey of the bright Circum QSO Medium (CQM) emission predicted around a large fraction of QSOs, using 2D imaging spectroscopy of targeted Type I and II QSOs. We will perform a Lyman alpha, a Star Formation Rate, and a mass selected survey of the CGM of galaxies over the redshift 0.01< z<1.1 range. Finally, we will search for emission from the cosmic webusing statistical techniques to explore the deepest sensitivity levels. Our mission utilizes demonstrated UV-sensitive photon-counting CCDs, UV optimized integral field spectrographs based on proven CWI designs, and an imaging channel with a new filter.

9905-14, Session 4

Development and performance of Si-drift-based detectors and their potential capability for x-ray astronomy *(Invited Paper)*

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The constantly evolving specifications for instrumentation to face X-ray space astronomy points towards extreme technical refinement of the

otherwise already high performances delivered by the various detectors technologies and the dedicated front end and read-out electronics. Besides the standard requirements for space applications, like the high readiness level and the probated radiation resistance, characteristics as: high efficiency in a range between few hundred eV to 10-15 KeV; high energy resolution and low leakage current at room temperature; high event rate per pixel; large sensitive areas up to more square meters; imaging capability and small pixel size, are imposing sometime contradictory constraints to the envisaged technologies. The proposed solutions will have to deepen in great details into a study of the whole harmonized detection system going from the mechanical layout to the detector's design geometry and production technology to the matching bonding techniques and not last the, on purpose, developed front-end electronics. This unavoidably leads towards specialized solutions leaving small space for generic developments. For a long time, the projects of detection systems for space applications have been profiting of the, sometime quite expensive, developments done for experiments at large accelerators. The specificity and harsh conditions on X-ray detection for astrophysics excludes at present this, in other times profitable, symbiosis. Expensive studies for dedicated detections systems shall be carefully planned in collaborative approach. Fully depleted Silicon junction detectors still offers best possible, if not ideal, solutions for soft X-ray detection. In particular the highly adaptive Silicon Drift Detectors design and production technology still plays a decisive role in the field of high performances X-rays detection systems. In this talk some recent front edge development and programmed evolutions will be discussed.

9905-15, Session 4

Properties of DePFET active pixel sensors fabricated on 200-mm wafers as monolithic focal plane detectors for x-ray astronomy missions

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DePFET active Pixel Sensors have been introduced as focal plane detectors for X-ray astronomy already in 1996, fabricated on high resistivity, back-illuminated fully depleted silicon, with fast and low noise operation. Since one year DePFET detectors are being fabricated in an industrial CMOS foundry maintaining the outstanding proven DePFET properties and adding new capabilities because of the use of state-of-the-art features of a modern CMOS fabrication process. We will highlight the additional features due to the new fabrication process (noise, speed, quantum efficiency, monolithic detector size, pixel sizes, implementation of new functions, such as gating, internal signal storage and repetitive non – destructive readout) and describe the constant progress achieved so far. In a first test technology run we have measured all device related properties, such as implantation profiles, backside protection, interface properties, leakage currents, depletion voltages etc. The most important features measured so far on the double-sided polished 725 µm thick 200 mm high resistivity float zone wafers were: (a) the thermally generated bulk leakage current was typically 500 pA per cm?, resulting in a noise contribution of less than one electron (rms) at – 60°C for a typical focal plane configuration. The operation voltage at full depletion was below 300 V reverse bias, in none of the 200 diodes measured a breakdown occurred. The surface and interface properties were excellent. The surface generated leakage current was below 400 pA per cm? at room temperature and the flat band voltage shift below 0.5 V giving hope for a very low 1/f noise contribution. The isolating gate oxides were sustaining a voltage of more than 100 V before breakdown - much more than needed. The smaller feature sizes in the chosen HV 0.35 µm CMOS process allows for pixel sizes of 20 x 20 µm? which is close to the diffusion limit for electrons in the 725 µm thick substrate. First measurements with DePFET devices will be shown from the fabrication ending early 2016.

A new fast gating and analog storage mechanism will be introduced enabling a fast switching between on and off state, (i.e. sensitive and insensitive state, gating) on the nanosecond scale. Proposals for potential focal plane configurations will be shown and their expected performance will be derived from the measured properties. We will present a concept for a device having a pixel size of 35 x 35 µm and a format of 2k x 2k pixels. It will exhibit a position resolution of better than 2 µm from 300 eV up to 20 keV resulting in 40k x 40k resolution points, still maintaining the good spectroscopic properties. A different design with 100 x 100 µm large pixels (ATHENA type), gatable with an analog storage capability will be shown as well. Being back-illuminated, the device exhibits high quantum efficiency from 100 eV up to 25 keV. A summary of the resulting new opportunities of this approach will be given.

9905-16, Session 4

Development of a Si/CdTe stacked detector system

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At the IAAT, we have built a stacked detector system consisting of a 64x64 DePFET-Matrix in front of a CdTe-Caliste module that can be operated under laboratory conditions that approximate the expected environment in space. The detectors were developed at the Max-Planck Institute Semiconductor Laboratory (HLL) in Neuperlach and the Commissariat à l'Energie Atomique (CEA) in Saclay, respectively.

The DePFET detector is made of a Si-based active pixel matrix that provides high count-rate capabilities with a near Fano-limited energy resolution up to 15 keV. The CdTe-Caliste module consists of a 1mm thick CdTe crystal with integrated readout electronics and builds a high performance spectro-imager with event time-tagging capability in the range between 2 keV and 250 keV.

In this combined structure the DePFET detector works as Low Energy Detector (LED) while the Caliste module - as High Energy Detector (HED) - detects predominantly the high energetic photons that have passed the LED.

Besides the high energy resolution over a large energy range, the setup can be used as a Compton camera and as an X-ray polarimeter. We present results of the performance achieved so far for these two applications. In addition, we studied side-effects like fluorescence emission or Compton scattering betweeen the two detector units that can easily be identified and analyzed.

9905-17, Session 4

Novel design for medical imaging Compton camera based on pixel Si/CdTe sensor *(Invited Paper)*

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The idea for the development of a Compton camera started in the 70s for use in astrophysics and soon after the idea was extended to the field of nuclear medicine. While the idea of the Compton camera is ingenious,

its construction is not straightforward. There are serious difficulties in constructing a fully operational camera that meets hospital standards and competes with Anger Camera. The two main problems are: an accurate reconstructions of the Compton cone, and subsequent image reconstruction. For the first problem, the Compton cone, one needs a detectors that is highly segmented, and with high energy resolution for both the scatterer and the absorber detectors. The 2nd problem is the image reconstruction from a set of Compton cones. Even with an ideal detector the image reconstruction still poses a serious limitation on the image resolution. The solution for the first problem is to use room temperature semiconductor detectors that can be high segmented into small pixels and at the same time have excellent energy resolution. Many groups have developed Compton camera prototypes based on pixel semiconductor detectors. However for such prototypes the Field Of View (FOV) is limited by the design and this poses a serious problem if one wants to increase the FOV to the nominal size of 54cm x 38 cm. The problem with image reconstruction can be minimized by using two cameras at 90 degrees.

The Voxel Imaging PET pathfinder project, has developed module detector, see image below, which is based on a stack of pixel CdTe detectors bonded to a dedicated ASIC. The module is made of a stack of 10 thin PCB layers, each with 4 detectors that constitute 4 x 100 voxel channels where each read-out voxel has a size of 1mm x 1mm x 2mm. Such a detector will provide precise and true 3D depth of interaction and high energy resolution which are fundamental parameters for defining the Compton cone. The module detector is being developed to be evaluated for use in a PET application and later for a Compton camera.

With such a module pointing to the object, under study, one can build a large FOV detector by stacking many of such modules together (next to each other and/or on top of each other). GAMOS simulations have shown that using a point source of 18F with such a camera one can achieve a sensitivity of 4.5 cps/kBq and a X,Y, and Z FWHM spatial resolution < 4mm.

9905-18, Session 4

Development of a portable Si/CdTe Compton camera for applications in diverse fields

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The Si/CdTe semiconductor Compton camera is a gamma-ray imager covering the band from a few tens keV to MeV. The camera was originally proposed to realize high-sensitivity observation to shed light on the sensitivity gap remaining in sub-MeV band in high-energy astrophysics. The Soft Gamma-ray Detector (SGD) onboard ASTRO-H is the one that was produced by our group based on the latest achievement represented by high-energy resolution Si and CdTe imaging sensors, low-noise multi-channel analog ASICs and highly-packed assembling techniques. The detail description of the SGD is reported in Watanabe et al. (NIM.A 2014) and Ichinohe et al. (NIM.A 2015).

The design concept of the Si/CdTe semiconductor Compton camera is reflected in its structure of highly-packed accumulation of high-energy and high-position resolution Si and CdTe imaging sensors. Remarkable efficiency can be obtained with compact detection system, for example, Si and CdTe sensors with a total active volume of 40 cm^{3} and 39.3 cm^{3} are installed in roughly 10 cm x 10 cm x 10 cm region of the SGD. In addition, since the effect of Doppler broadening is smaller in the Si devices than in other semiconductor devices, the camera allows the difference between the measured and actual scattering angles to be constrained, meaning that higher angular resolution is expected. Actually, good angular resolution of 2.5 degree (FWMH) at 511 keV was measured in our preceding research (Takeda et al. SPIE 2007).

ASTROCAM is the first commercial Compton camera based on design and manufacturing resources of the SGD. Through field tests in Fukushima, we demonstrated that the camera is capable of hot spot detection and the evaluation of radioactive decontamination (Takeda et al. NIM.A 2015). The standard model of the camera consists of 8 layers of Si detectors and 4 layers of CdTe detectors. It is possible to integrate more detectors, up to 32 layers of Si and 8 layers of CdTe detectors. In addition, all four horizontal directions of the accumulated detectors are covered by 2 layers of CdTe modules. In this enhanced model, the efficiency is improved to 2.8 cps/MBq at 1 m (137-Cs, 662 keV), which is about 16 times higher than that of the standard model. The energy resolution of the camera is measured to be 2.2% (FWHM) for 662 keV gamma-rays. A moderate angular resolution of 5.4 degree (FWHM) in ARM (Angular Resolution Measure) is obtained, meaning that it has about 1 m spatial resolution at 10 m from the camera. The basic specifications of ASTROCAM are summarized in the technical review (http://www.mhi-global.com/company/technology/review/pdf/e511/e511068.pdf).

Higher angular resolution of the Si/CdTe semiconductor Compton camera than ever Compton cameras might open up new possibilities in medical imaging. The resolving power better than 3 mm was experimentally demonstrated for a 364 keV (131-I) gamma-ray with the first medical prototype camera (Takeda et al. IEEE 2009). More practical imaging with a mouse was performed and iodinated (131-I) methylnorcholestenol and 85-SrCl_{2} solution injected into the mouse are successfully visualized (Takeda et al. IEEE 2012). Now we are developing a new device for tracking of a recoiled electron by Compton scattering in order to perfectly solve Compton kinematics and change the cone-shaped probability distribution of a incident gamma-ray into single direction.

9905-19, Session 4

Fast event recognition for x-ray silicon imagers

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New generations of X-ray observatories are being planned with collecting areas more than an order of magnitude larger than current observatories, with silicon imagers featuring high speed readout to prevent photon pileup. These detectors require rapid event processing to discriminate between X-ray events and particle background. We will discuss the design and status of a fast readout event recognition board based on a Virtex 5 FPGA we are developing with funding from NASA's Strategic Astrophysics Technology program.

9905-20, Session 4

Development of wide-field low-energy x-ray imaging detectors for HiZ-GUNDAM mission

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Institute of Technology (Japan); Satoshi Hatori, Kyo Kume, Takashi Hasegawa, Satoshi Mizushima, The Wakasa Wan Energy Research Ctr. (Japan)

We are planning a future gamma-ray burst (GRB) mission HiZ-GUNDAM to probe "the end of dark ages and the dawn of formation of astronomical objects", i.e. the physical condition of early universe beyond the redshift of z > 7. Especially we will focus on the history of first and second generation star formation activity, cosmic reionization and chemical evolution of heavy elements. We are now developing a wide field low energy X-ray imaging detectors to observe high redshift GRBs, which cover the energy range of 1 < E < 20 keV. We can obtain the X-ray images with orthogonally placed two sets of 1-dimensional coded aperture mask systems. We use silicon strip detectors (SSDs) as X-ray imaging sensor. One of the key technologies for X-ray imaging detector is multi-channel readout methods. We developed readout analog ASICs, named ALEX (ASIC for Low Energy X-ray), are specifically designed to read out small charge signals from SSDs with high gain at pre-amplifiers. ALEX can simultaneously read out 64 signal channels. It is important to understand characteristics of individual channel in order to adjust their performance to be uniform. We investigated baseline voltages, gains, and noise levels for all readout channels. Applying several adjustments with internal digital-to-analog converters, we succeeded in making the baseline voltage uniform within the standard deviation of 34 eV. We performed several radiation tolerance test for ALEX with proton and ion beams at Wakasa-wan Energy Research Center and strong gamma-ray sources at Tokyo Institute of Technology in Japan. We confirmed that ALEX can keep working during 10 years if ALEX are exposed to protons in the low earth orbit. Now we are developing a prototype model of X-ray imaging detectors with the detector area of 50 cm2, 1,024 strips, and 16 readout ALEX chips as well as dedicated digital electronics. SSD and ALEX are directly connected with short bonding wires to minimize the noise level. We achieved the detection threshold is 1.5 keV and the energy resolution of 1 keV. We also performed X-ray imaging experiments with six meter beamline in our laboratory, and confirmed the localization accuracy is 5.7 arcminutes. In this presentation, we report overview of small prototype model system of wide field X-ray imaging detector onboard HiZ-GUNDAM, and show performances of ALEX series.

9905-136, Session PS1

Correcting for distortions due to walk and geometric distortion in the COS FUV detector

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The Far Ultraviolet detector of the Cosmic Origin Spectrograph (COS) on the Hubble Space Telescope (HST) is subject to distortions on a range of spatial scales in its two-dimensional format due to its analog nature. Incomplete correction of these effects can lead to errors in wavelength scales and flux measurements in the calibrated spectra. Two of the largest sources of error are geometric distortion and walk. Although they are accounted for separately in the CalCOS calibration pipeline, they are highly coupled and can be considered as manifestations of the same effect.

The current calibration pipeline does not apply any walk correction in the dispersion direction even though walk-induced errors can be more than a resolution element in some cases. The current geometric correction, which was derived without considering walk effects, is also known to have inaccuracies. As part of our efforts to improve the wavelength calibration of COS, we have revisited the existing walk and geometric correction using both prelaunch and on-orbit data. We present the results of these studies, our plans for changes to CalCOS and its reference files, and the expected improvements to the final data products.

9905-137, Session PS1

In-flight performance of the polarization modulator in the CLASP rocket experiment

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We developed a polarization modulation unit (PMU), a motor system to rotate a waveplate continuously. In polarization measurements, the continuous rotating waveplate is an important element as well as a polarization analyzer to record the incident polarization in a time series of camera exposures. High rotation uniformity for the motor is required to reduce errors in a polarization measurement. To achieve this in the next Japanese solar observation satellite SOLAR-C, the control logic of PMU was originally developed by the SOLAR-C working group. We applied this PMU for the Chromospheric Lyman-alpha SpectroPolarimeter (CLASP). CLASP is a sounding rocket experiment to observe the linear polarization of the Lyman-alpha emission (121.6 nm vacuum ultraviolet) from the upper chromosphere and transition region of the Sun with a high polarization sensitivity of 0.1% for the first time, and then to estimate their vector magnetic field by the Hanle effect. The waveplate motor (PMU-ROT) and its driver (PMU-DRV) were developed to optimize the rotation for the CLASP waveplate (12.5 rotations per minute). Rotation non-uniformity of the waveplate causes error in the polarization degree (i.e. scale error) and crosstalk between Stokes components. We confirmed that PMU has superior rotation uniformity in the ground test. In that test, we constructed the polarization measurement system similar to the CLASP instrument with a waveplate on PMU and a polarization analyzer. By obtaining a polarization modulation curve with the system and comparing to the ideal curve, we confirmed that the scale error and crosstalk of Stokes Q and U are less than 0.01 %. PMU-DRV has a function to send exposure triggers to the CCD cameras, which were developed by NASA, for synchronizing their exposures to the waveplate angle. PMU-DRV also sends the angle error signal for the telemetry, and we can check the performance by the signal. After PMU was attached to the CLASP instrument, we performed two vibration tests: once in Japan before the shipment to U.S. and the other at the launch site in U.S. We confirmed all PMU functions performance including rotation uniformity did not change after either vibration test by the angle error signal. CLASP was successfully launched on September 3, 2015, and PMU functioned well as designed. According to the PMU flight status (e.g. angle error), PMU achieved a good rotation uniformity during all of the observation period similar to the ground tests, and the high precision polarization measurement of CLASP was successfully achieved. In this presentation, we report the overview of PMU, and performance n!ot only from the ground tests but also from the flight.

9905-138, Session PS1

The re-flight of the Colorado high-resolution Echelle stellar spectrograph (CHESS): improvements, calibrations, and post-flight results

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In this proceeding, we describe the scientific motivation and technical development of the rocket-borne Colorado High-resolution Echelle Stellar Spectrograph (CHESS), focusing on the hardware advancements and testing supporting the second flight of the payload (CHESS-2). CHESS is a far ultraviolet (FUV) rocket-born instrument designed to study the atomic-to-molecular transitions within translucent cloud regions in the interstellar medium (ISM). CHESS is an objective echelle spectrograph with f/12.4 and resolving power of > 100,000 over the band pass 102 – 170 nm. The spectrograph was designed to employ an echelle grating with a groove density of 69 lines/mm. The fabrication of this grating has been an ongoing research and development (R&D) program comparing several lithographic and electron-beam etching techniques. We compare the performance of R&D echelle etching processes with mechanically-ruled echelle gratings in the FUV. Given the poor performance of the lithographic and electron-beam etched optics, CHESS-2 will utilize a mechanically-ruled, lower groove echelle density (52.9 grooves/mm – observed orders in CHESS-2: 340 – 210) fabricated at Bach Research Inc. The cross-dispersing grating, developed and ruled by Horiba Jobin-Yvon and launched on CHESS-1, is a holographically-ruled, low line density (351 grooves/mm), powered optic with a toroidal surface curvature. Both gratings were coated with Cr+Al+LiF at Goddard Space Flight Center (GSFC). We measure the reflectivity and efficiency of both the flight gratings across the 90 – 165 nm bandpass at the University of Colorado. Results from final efficiency and reflectivity measurements for the optical components of CHESS-2 will be presented, with comparison to optical performance from CHESS-1. Additionally, CHESS-2 will be the second launch of the 40mm diameter cross-strip anode readout microchannel plate (MCP) detector fabricated by Sensor Sciences to achieve high resolution over a large format (16kx16k format, 25 micron spectral resolution with 2.5 um digital pixels) with photon-counting performance at high count rates (global rates ~ 1 MHz). We will present pre-flight sensitivity and effective area calculations, as well as laboratory spectra and instrument calibration results. The launch of CHESS-2 is scheduled for February 2016 aboard NASA/CU sounding rocket mission 36.297 UG. We will observe the sightline to the hot star ? Per to diagnose the column densities, temperature, and kinematics of atomic and molecular species in the ISM.

9905-139, Session PS1

The SwRI ultraviolet reflectance chamber (SwURC): status report on a far ultraviolet reflectometer

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The Southwest Research Institute Ultraviolet Reflectance Chamber (SwURC) is a state of the art UV reflectometer chamber and data acquisition system that can measure the bidirectional reflectance from 115 to 180 nm over various reflectance angles in the principal plane. UV reflectance spectroscopy is a very important tool for studying airless planetary surfaces. However, few laboratory measurements of the far-UV spectral signatures of common minerals and ices exist, and of the measurements that do exist most were only conducted at one reflection angle with poor wavelength sampling. This lack of laboratory measurements of materials has limited the precise interpretation of remote sensed UV data from the Moon, asteroids, comets, etc. The SwURC provides laboratory-based UV reflectance measurements of water frost/ice, lunar soils, simulants, and analogs in support of interpretation of UV reflectance data from current UV space instruments, including Lunar Reconnaissance Orbiter (LRO) Lyman Alpha Mapping Project (LAMP), and New Horizons and Rosetta Alice imaging spectrographs. We report the recent radiometric calibration results from measuring the specular reflection of Al/MgF2 coated mirrors and the diffuse reflectance of Fluorilon as well as UV spectral reflectance measurements planned and in progress for water ice, lunar simulants, and Apollo soil sample 10084.

9905-140, Session PS1

Alignment and calibration of the ICON-FUV instrument: development of a vacuum UV facility

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In the frame of the ICON mission, CSL has developed a vacuum UV facility to align and characterize the FUV instrument. This FUV instrument is based upon the IMAGE Spectrographic Imager (SI) [Mende et al., 2000c]. Like its predecessor, ICON-FUV, is a two-channel imager that uses a grating spectrometer for spectral discrimination. The two channels are required to provide the daytime profiles of two wavelengths characterizing the N2 and O species. This grating type of spectrographic imager minimizes contamination by out-of-band light leaks that are a typical problem for non-grating type FUV cameras.

The facility developed at CSL is working under vacuum UV from 100 nm to visible light. It provides a large collimated UV beam covering the entire entrance slit of the instrument. The instrument is placed on a large tip/tilt and rotation stages. This MGSE provides the ability to rotate the instrument around the entrance pupil and covers more than the entire FOV of the instrument [24° vertical, 18° horizontal].

This paper will present the complete calibration setup and related optical simulations, the results of the alignment campaign first and the calibration next. The calibration facility is based on the combination of a double sources (Deuterium, and white laser) connected to a vacuum Mc Pherson monochromator. The light going out of the exit slit of the monochromator illuminates a pin-hole and a MgF2 diffuser to create an extended source for the collimator. The collimator is based on an off-axis parabola which produces approximately a 10 cm diameter collimated beam. Another important feature is a switchable beam divergence. This is made possible by using a wheel with different sized pinholes and a position-controllable off axis-parabola thanks to a motorized translation stage. Therefore, one or more pixels of the instrument cameras can be enlightened. The possibility to have several illuminated pixels speeds up, facilitates and improves the centroidization process.

The control of the line of sight during the thermal cycle qualification campaign is enabled by an auto-collimation process with the help of a mirror cube and CMOS camera in the visible domain. This one is using reflection by a reference cube placed on the instrument turret structure (scanning mirror). The light reflected by the reference cube returns back into the collimator and is focused into the camera.

Specific strategies have also been developed to align the instrument under vacuum to meet spectral properties and imagery requirement. Three of the instrument mirrors were actuated to align the instrument under vacuum. Simulation and alignment achievements will be presented.

9905-141, Session PS1

The qualification campaign of the EUI instrument of solar orbiter

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The Extreme Ultraviolet Imager (EUI) instrument is one of the ten scientific instruments on-board the Solar Orbiter mission to be launch in October 2018. It will provide full-sun and high-resolution images of the solar corona in the extreme ultraviolet (17.1 nm and 30.4 nm) and in the vacuum ultraviolet (121.6 nm).

The validation of the EUI instrument design has been completed with the Assembly, Integration and Test (AIT) of the instrument two-units Qualification Model (QM). Optical, electrical, electro-magnetic compatibility, thermal and mechanical environmental verifications were conducted and are here summarized. The integration and test procedures for the Flight Model (FM) instrument and sub-systems were also verified.

Following the Qualification Review, the flight instrument activities were started with the assembly of the flight units. The mechanical and thermal acceptance tests and an end-to-end final calibration in the (E)UV will then be conducted before delivery for integration on the Solar Orbiter Spacecraft by end of 2016.

9905-142, Session PS1

Full-Stokes polychromatic polarimeter design for Arago

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The UVMag consortium will propose the Arago space mission to the ESA call Cosmic Vision M5. This mission aims at characterizing all kind of stars and their environment simultaneously, to better understand the cycle of matter in our galaxy. It carries a single instrument, a spectropolarimeter, acquiring data from 119 nm to 888 nm and enabling the determination of the magnetic field of the stars thanks to the Zeeman effect. One of the key instrumental point of this project is the development of an efficient polarimeter over the large spectral range and in space. We chose to use a polychromatic temporal modulation to achieve a measurement of all four Stokes parameters: I the intensity, Q and U the linear polarization states, and V the circular polarization. The modulator is composed by several birefringent Magnesium Fluoride plates, optimized to achromatize the extraction efficiency of the Stokes parameters from FUV to NIR. This polarization modulator is followed by a polarization beam-splitter to analyze the state of the light. After the polarization analysis, the light goes through a high-resolution spectrograph.

The theoretical optimization and design of the polarimeter and of the whole instrument will be presented, as well as the first laboratory results on this concept.

9905-143, Session PS1

UVESP: ultraviolet visible Echelle spectropolarimeter for stellar astrophysics

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In this contribution, we describe the optical design of UVESP, an efficient instrument designed for mid resolution (30,000) spectropolarimetric observations in the 119-888nm wavelength range. Spectropolarimetry introduces challenging constraints in the image quality of the echellé design that are addressed via the introduction special optical elements.

In the current design, the spectrograph is fed by the radiation of an F10 telescope that goes through an on-focus polarizer used to analyse the incident beam. The design has been optimized for the parameters of the ARAGO mission; the polarizer splits the incoming beam into two states of polarization that extend over 400 microns at the entrance of the spectrograph; ideally the spectrograph magnification must be >0.5 to guarantee a good separation between the two polarized states.

At the entrance of the instrument, a beam splitter divides the beam into the ultraviolet (UV) and the visible (VIS) channels with target wavelengths 355 nm to 888 nm for the VIS channel and 119 to 320 nm for the UV channel.

In the VIS channel the beam continues to the slit and then a collimator is placed in order to illuminate a prism with a collimated beam. After the prism an Echellé-grating is allocated. The beam has a double pass by the prism. The cross-dispersion is made with a concave diffraction grating. After the grating, objective lenses are allocated.

In the UV channel the beam continues from the slit to a collimator mirror. After, an Echelle-grating and a cross- dispersion grating are allocated.

This design is significantly optimized with respect to previous similar instruments, such as the spectrograph proposed for the UVMag mission, and it is the current baseline spectropolarimeter for the ARAGO mission.

9905-144, Session PS1

Simulations of the WUVS instrument

Pablo Marcos-Arenal, Ana Inés Gómez de Castro, Gracia Belén Perea Abarca, Univ. Complutense de Madrid (Spain); Mikhail Sachkov, Institute of Astronomy (Russian Federation)

The World Space Observatory - Ultraviolet (WSO-UV) is an international space telescope to observe in the ultraviolet (UV) range. The WSO-UV spacecraft is equipped with the instrument WUVS (WSO UltraViolet Spectrograph) that provides high resolution spectroscopy (R~55,000) in two channels: VUVES and UVES. VUVES is a far UV echelle spectrograph designed to observe point sources in the range 1020-1800 Å. UVES is the near UV echelle spectrograph, working in the range 1740-3100 Å.

The performance of these instruments can be evaluated through simulations of the expected observation.

WUVS instruments are high-precision spectrographs whose expected performance must be evaluated carefully from an appropriate overall instrument model. Since it is not feasible to build and test a prototype of a space-based instrument, numerical simulations performed by an end-to-end simulator are used to model the noise level expected to be present in the observations. The performance of the instrument can be evaluated in terms of noise source response, data quality, and fine-tuning of the instrument design for different types of configurations and observing

strategies. The simulator should also allow for testing the feasibility of the scientific programs and as a preparatory step for the scientific data processing. The WUVS simulator tool has been developed for the validation of the expected instrumental response..

In this work, we describe the implementation details of this tool and the noise models applied in the WUVS Simulator. The WUVS Simulator has been implemented as a further development of the PLATO Simulator, adapting it to an echelle spectrograph and the WUVS instrument specific characteristics.

The PLATO Simulator is an end-to-end simulation software tool designed for the performance of realistic simulations of the expected observations of the PLATO mission but easily adaptable to similar astronomical missions incorporating CCD detectors. The PLATO Simulator is an open source code developed by the Institute for Astronomy at KU Leuven. The original code required several modifications to be used for VUVES and UVES that are thoroughly described in this article.

The WUVS simulator is designed to generate synthetic time series of CCD images by including models of the CCD and its electronics, the telescope optics, the jitter movements of the spacecraft and all important natural noise sources.

We provide a detailed description of several noise sources and discuss their properties, in connection with the optical design, the quantum efficiency of the detectors, etc. The expected overall noise budget of the output spectra is evaluated as a function of different sets of input parameters describing the instrument properties.

9905-145, Session PS1

Fireball multi object spectrograph: as-built optic performances

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Fireball (Faint Intergalactic Redshifted Emission Balloon) is a NASA/CNES balloon-borne experiment to study the faint diffuse circumgalactic medium from the line emissions in the ultraviolet (200 nm) above 37 km flight altitude. The payload and gondola have been integrated and calibrated for the 2016 flight. Fireball relies on a Multi Object Spectrograph (MOS) that takes full advantage of the new high QE, low noise 13.5 ?m pixels UV EMCCD. The MOS is fed by a 1 meter diameter parabola with an extended field (1000 arcmin2) using a highly aspherized two mirror corrector. All the optical train is working at F/2.5 to maintain a high signal to noise ratio. The spectrograph (R~ 2200 and 1.5 arcsec FWHM) is based on two identical Schmidt systems acting as collimator and camera sharing a 2400 g/mm aspherized reflective Schmidt grating. This grating is manufactured from active optics methods by double replication technique of a metal deformable matrix whose active clear aperture is built-in to a rigid elliptical contour. We will present the as-built optic performances of the Fireball instrument.

9905-146, Session PS1

Ultraviolet cosmic imager to study bright UV sources

Joice Mathew, Ajin Prakash, Mayuresh N. Sarpotdar, Margarita Safonova, Jayant Murthy, Sreejith Aickara Gopinathan, Indian Institute of Astrophysics (India)

We have designed and developed a compact ultraviolet imaging payload to fly on a range of possible platforms such as high altitude balloon experiments, cubesats, space missions, etc. The primary science goals are to study the bright UV sources (mag < 10) and also to look for transients in the Near UV (200- 300 nm) domain. Our first choice is to place this instrument on a spacecraft going to the Moon as part of the Indian entry into Google lunar X-Prize competition. The major constraints for the instrument are, it should be lightweight (< 2 Kg), compact (length < 50 cm) and cost effective. The instrument is an 80 mm diameter Cassegrain telescope with a field of view of around half a degree designated for UV imaging. In this paper we will discuss about the various science cases that can be performed by having observations with the instrument on different platforms. We will also describe the design, development and the current state of implementation of the instrument. This includes opto-mechanical and electrical design of the instrument. We have adopted an all spherical optical design which would make the system less complex to realize and a cost effective solution compared to other telescope configuration. The structural design has been chosen in such a way that it will ensure that the instrument could withstand all the launch load vibrations. An FPGA based electronics board is used for the data acquisition, processing and CCD control. We will also briefly discuss about the hardware implementation of the detector interface and algorithms for the detector readout and data processing.

9905-147, Session PS1

A near ultraviolet solar-blind telescope design using silicon CCD detectors

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We propose a novel approach to constructing a solar-blind near ultraviolet telescope using specialized mirror coating. Each mirror in a three (or four) element optical system has a coating reflective in the 200-300nm bandpass and transmissive at wavelengths longer than 300nm. This telescope can therefore use CCD detectors providing high quantum efficiency, low noise, and a large pixel count. We have procured, from Materion Corporation, sample coatings with greater than 90% reflectance in the 200-300nm bandpass and less than 10% at wavelengths longer than 300nm. With three surfaces, these coatings provide >75% in band transmission for a telescope with better than 10,000 rejection at visible wavelengths. The use of ultraviolet optimized CCD detectors, combined with a three or four element telescope, would enable an Explorer class mission with near ultraviolet survey efficiency more than 100 times that of the recent GALEX mission. We will present measured reflectance and transmission curves from 200 - 1000nm for multiple samples. We will also show simulations of the expected performance of both 3 and 4 mirror systems combined with measured e2v CCD detector performance for a conceptual space mission.

9905-148, Session PS1

Concept study for a compact homodyne astrophysics spectrometer for exoplanets (CHASE)

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Here, we describe the concept study for designing and developing a new compact, high-performance, high spectral resolution ultraviolet (UV) spectrometer for astrophysics science of wide applicability to NASA sounding rockets, International Space Station (ISS) and Astrophysics missions, Discovery and New Frontiers including those of cosmology and

exoplanets employing orbiting spacecraft, deep space missions, NanoSat or SmallSat deployments.

Exoplanet science is now in its full expansion, particularly after the CoRoT and Kepler space missions. However, lack of data and knowledge of temporal variations in the parent star's stellar spectra and abundance of key photochemical species (e.g., O3, H2O, CO, etc.) in exoplanets has confined our detailed understanding to develop precise models of the exoplanet atmospheric chemistry. To address this, we need simultaneous observations at more than one wavelength region especially in near-ultraviolet (NUV) and far-ultraviolet (FUV). But so far the UV observations are done by HST, and nothing is planned after HST retires in 2019.

In this study, we are targeting to build a new instrument to sequentially observe exoplanet atmospheres and their parent's stellar spectra over a significant time in NUV and FUV. The Compact Homodyne Astrophysics Spectrometer for exoplanets (CHASE) offers integrated spectra over a wide field-of-view (FOV~40arcsec) in high spectral resolution (R>105) in a miniaturized architecture using no (or a small < 1m) primary mirror. The architecture of CHASE combines the high étendue of a Fourier Transform Spectrometer (FTS) with higher optomechanical tolerance and simpler optomechanical design associated with grating spectrometers. With an all-reflective optical design, CHASE will target specific spectral features in NUV and FUV of multiple gases of exoplanet atmospheres. CHASE's wide FOV is compatible with the relaxed pointing requirements of current CubeSats and SmallSats which makes it readily qualifiable for space in a compact format and have the potential to enable major scientific breakthroughs.

Various configurations of instruments similar to CHASE have been developed as proof-of-concept laboratory prototype, ground-based instrumentation, and sounding rocket experiments in the Optical, NUV and FUV wavelengths. These studies have demonstrated high R and high sensitivity UV spectrometers can be built in ultra-compact configurations similar to CHASE with no or small aperture telescope for a variety of space science applications.

9905-149, Session PS1

Numerical simulations of space UV spectrographs

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The aim of our work was modelling of spectrum images of far and near UV spectrographs and Long slit low resolution spectrograph of WSO-UV mission. We pay special attention to angular energy distribution of both difraction gratings, echelle and cross dispertion. A code was realised by using C++ language and nVidiaCUDA technology. The model consists of 3 independent modules: beam trassing module, enegy efficiency estimation module and CCD image simulator. Spectrographs' optical element parameters (surface, distances, grating density, reflectance and refraction coefficients etc.) were used as input parameters. As a result we get spectrum image in FITS format for selected detector. We implemented our model for detector coating masks for WSO-UV spectrographs. The model was verified by comparing observed and simulated spectra of NES spectrograph of the Russian 6-m telescope.

9905-150, Session PS1

WSO-UV ground segment for observation optimization

Mikhail Sachkov, Institute of Astronomy (Russian Federation); Olga Basargina, Yury Kazakevich, NPO Lavochkin (Russian Federation)

The WSO-UV Ground Segment (GS) provides the means and resources to manage and control the mission, to receive and process the data produced by the instruments and to disseminate and archive the generated products.

Furthermore it provides a single interface to the users to allow optimum utilization of the system resources in line with the user needs. GS is comprised by all the infrastructure and facilities involved in the preparation and execution of the WSO-UV mission operations, which typically encompass real-time monitoring and control of the spacecraft, telescope and instruments as well as receiving, processing and storage of the scientific data. There will be two complete GS systems: in Russia and in Spain. The elements of GS are: Ground Station Monitoring and Control System, Mission Operations Center and Science Operations Center.

9905-151, Session PS1

Optical design of WUVS instrument: WSO-UV spectrographs

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The optical design of WSO-UV mission spectrographs (WUVS instrument) is presented. World Space Observatory - Ultraviolet project is an international space observatory for spectroscopy and imaging in 115-310 nm spectral range. The whole spectral range should be observed with the help of two high-resolution echelle spectrographs, for Far-UV (110-180 nm) and Near-UV (178-320 nm) domains accordingly. The third channel is the Long Slit Spectrograph that incorporates both the UV and VUV wavelength range. The main changes with respect to the previous design have been: a) the cross disperser in the UVES spectrograph is now similar to the VUVES spectrograph (based on the cross disperser combined with a UV camera mirror) and b) segmented toroidal gratings are implemented in the LSS design. CCDs were chosen as detectors for all 3 channels. In this optical design basic schemes of the VUVES and UVES spectrographs are quite similar.

Each of the three spectrographs has its own entrance slit, lying in the focal plane of the T-170M telescope on a circle with diameter of 100 mm. The three optical trains are not used for simultaneous observation, but in sequential mode. This is managed by satellite motion.

9905-152, Session PS1

Design of a wide field far-UV spectrometer for a mission to Mars

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An imaging spectrometer for observations of the Martian corona and the

Martian thermosphere is presented. The corona extends over 10 Martian radii and its measurement requires observations over a very wide field. The spectrometer covers the wavelength region 120-170 nm where this band includes coronal spectral lines of Ly alpha and oxygen, and thermospheric spectral lines from ionized oxygen and carbon and the 4th positive band of CO. Stellar occultation observations will provide atmospheric density measurements. These scientific requirements are fulfilled by an Offner-type spectrometer with a 110 degree instantaneous field of view and no moving mechanisms. Both the spectral and imaging resolution vary across the field, from higher resolution across the planet body, to lower resolution required at the diffuse outer parts of the corona. This Offner-type design has not been previously used in the FUV.

9905-153, Session PS1

Near UV imager with an MCP-based photon counting detector

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Small Scientific payloads below 10 kg can be designed and developed easily and flown on available flight opportunities like high-altitude balloons or CUBESATs. We are developing a compact UV Imager using a light weight optical system and a photon counting detector with off-the-shelf MCPs, CMOS sensor and electronics. The lens system is designed in such a way that it provides an aberration free image over a wide field of view. Micro channel plate (MCP) based detectors are widely used in the ultraviolet region due to their low noise levels, high sensitivity and better spatial and temporal resolution. We are using a Z stack MCP with a compact High Voltage Power Supply and the readout is done using a phosphor screen anode. The scientific goals behind the payload are to observe bright solar system objects and transient detection. In addition the photocathode of the MCP has good spectral response till below 2000 A°, which makes it possible to study some of the extinction features like the 2175 A° bump with suitable designed optics and filters. The detector is designed to be capable of working in direct frame transfer mode as well in photon-counting mode for single photon event detection. The identification and centroiding of each photon event is done using an FPGA (Field-Programmable Gate Array)-based data acquisition and a real-time processing system.

9905-154, Session PS1

Response of a spaceborne lightweighted optical system to various forms of thermal expansion inhomogeneity

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Elsewhere we have discussed the role of thermal expansion and thermal diffusion in materials for spaceborne mirrors. In these cases, we assumed an ideal material with perfect homogeneity for example in thermal expansion. Some materials considered for these mirrors exhibit inhomogeneity of thermal characteristics, and this manifests into optical figure errors when exposed to thermal transients and offsets operational temperatures. We will examine the effect on optical figure as several different forms of inhomogeneity of thermal expansion are considered. We will address both slab mirrors and lightweighted mirrors.

9905-155, Session PS1

Spectral calibration of CCDs and multilayer filters intended for future space applications

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We have examined spectral sensitivity of CCD matrices (typically 1024?2048 pixels, 13 ?m pixel size) in a wide wavelength range: from 110 nm to 600 nm. Some of the CCD matrices under study apply to VUV operating range, and some will handle soft X-ray spectral images. The distant goal is to employ the CCD matrices as a part of future telescopes for remote Earth ionosphere observations and for soft X-ray solar missions. Therefore, it is meaningful to understand which spectral sensitivity the CCD detectors have in a wide spectral range.

In the range of 300-600 nm we used a prism monochromator with a halogen lamp as a source of light. We also took an IRD silicon detector with known quantum efficiency as a calibrated detector. The results of calibration have relative error about 5% that is enough to estimate total power of useful or unwanted radiation in the waveband accounted.

In the 250-300 nm UV spectral range we also used a prism monochromator, here employing a deuterium lamp as a source of radiation. We used a photomultiplier tube as a detector to calibrate the CCDs in the current spectral region with reasonable spectral resolution.

All measurements in the waveband 110-250 nm we have conducted inside the IKAR vacuum chamber due to significant absorption of the VUV radiation in the air. The inner dimensions of the vacuum chamber are Ø 0.9 m ? 3.8 m. It is equipped with a turbopump enabling 'dry' evacuation to a residual pressure of ~ 5·10–5 Torr.

We have developed a VUV spectrograph and mounted it on a 0.6 m ? 3.6 m optical table inside the IKAR vacuum chamber. We employed a laser-driven plasma source of VUV radiation emerging under irradiation of a tungsten target by laser pulses (Nd:YAG, 1 J, 8 ns, 1064 nm). A heavy flint lens in the scheme focuses the laser beam onto the target into a focal spot with effective area Seff ~ 10–4 cm2. The peak radiation intensity reaches 10^12 W/cm2. Such laser-plasma radiation source possesses a quasicontinuous spectrum covering wavelengths from 5 nm to the visible spectral range. We have blocked the XUV radiation in the waveband 5-110 nm using a MgF2 spectral filter.

The VUV spectrograph inside the vacuum chamber comprises an entrance slit, a MgF2 spectral filter, a wide-aperture transmission diffraction grating with noticeable supporting structure, and a detector. In the stage of CCD calibration in the waveband 110-250 nm we used an IRD UV photodiode as a reference detector. The electrical output of the photodiode led to an oscillograph outside the vacuum chamber.

Having the CCD calibrated, we have measured the initial spectral effectivity of our tungsten laser-plasma radiation source in the 110-250 nm waveband using the same spectrograph. Then we employed the calibrated spectrograph to measure spectral transmittance functions of several VUV multilayer filters intended for use inside the future telescopes for remote Earth ionosphere observations. Each filter has a multilayer structure deposited on MgF2 glass plate Ø 40 mm.

9905-157, Session PS1

Advanced telescope mirror coatings for ultra violet astronomy: challenges and opportunities

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Advanced space telescopes to study astrophysical phenomena in the far ultraviolet to near infrared require mirror coatings that will gather enough light in the entire spectrum. While coatings for the optical and near IR part of the spectrum are fairly well developed with proven systems, the far ultraviolet presents significant challenges. Typical Aluminum mirrors protected with MgF_2 fall short of the requirements below 120nm. Therefore new and improved coatings are sought to protect aluminum from oxidation that causes severe absorption. Besides choice of materials, the process of applying coatings has to be optimized and controlled accurately and reliably to ensure the coatings preserve the expected optical characteristics. This challenge is addressed here with experimental investigations at JPL and at GSFC. Conventional and atomic layer deposition processes are explored. We present the progress achieved to date and discuss the path forward to achieve high reflectance in the spectral region from 90 to 130nm without degrading performance in the visible and NIR regions, taking into account durability concerns when the mirrors are exposed to normal laboratory conditions.

9905-158, Session PS1

A technique for selectable band imaging in the ultraviolet and optical

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We present a design concept that provides selectable band imaging in the optical and ultraviolet. The bandpass is created through reconstructive spectroscopy, utilizing crossed gratings, and creates an image, not a spectrum. The bandpass depends upon the field of view, the object location within that field, and the illuminated area of the second grating. All three factors are in principle selectable in real time, so that an instrument utilizing this technique is extremely flexible in its application. The technique utilizes no transmitting optics, and therefore is usable down to the limits of normal incidence reflectivity (~ 400 Å).

9905-159, Session PS1

Optical alignment of the chromospheric Lyman-Alpha spectropolarimeter using sophisticated methods to minimize activities under vacuum

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The Chromospheric Lyman-Alpha Spectro-Polarimeter (CLASP) is an international sounding-rocket project aiming to achieve polarimetry of the Lyman-alpha line (121.6nm) with unprecedented 0.1% polarization accuracy. However, achieving the spatial and spectral resolutions (3.2'' and 0.01nm, respectively) are also crucial to resolve the fine structures of the solar upper-chromosphere and lower transition region, as well as resolving the Lyman-alpha line profile. A careful alignment of the optical elements composing the Cassegrain telescope and the inverse Wadsworth mount spectro-polarimeter was required, but aligning an instrument at Lyman-alpha implies working under vacuum condition since this wavelength is absorbed by air, which makes any experiments difficult. Therefore, an alignment procedure was investigated to minimize the activities under vacuum.

The telescope (270mm aperture diameter and 2614mm focal length) was aligned by measuring its wavefront error in a double-pass configuration with a He-Ne (632.8nm) laser-interferometer. Interference fringes were obtained even though the "cold mirror" coating on the primary mirror reflected only 3.5% of the visible light on each of the two reflections. The secondary mirror tilt and despace were adjusted in order to remove the coma and defocus aberrations at the center of the slit. After the alignment, the wavefront error was measured in "zero-g" condition by performing measurements with different orientations of the telescope to cancel the effect of gravity, and was used to estimate the point spread function at the center of the slit. Additional wavefront error measurements were also conducted across the field of view by adjusting the position of the laser interferometer with a 6-axis table. As a result, a 8.0 microns RMS spot radius was evaluated even at the edge of the slit (requirement: 13.0 microns).

The spectro-polarimeter is composed of a grating that diffracts the incident light from the slit to the +/– first order light in Lyman-alpha, two off-axis parabola mirrors that focuses the diffracted light, and two cameras imaging the Lyman-alpha spectra. The optical alignment aimed to adjust the tilts and rotation of the grating, the tilts of the off-axis mirrors and the CCD camera positions (i.e. focus adjustment). The off-axis mirrors were aligned at first in visible-light using a custom grating (hereafter alignment grating) specially designed with the same diffraction angle in the He-Ne wavelength as that for the flight grating in the Lyman-alpha. The tilt of the off-axis mirrors was adjusted by estimating the misalignment from the shape of the spot images formed by a pinhole array located at the slit position and illuminated by a He-Ne laser. The resulting RMS spot radius at the edge of the slit was estimated around 11.0 microns (requirement: 13.5 microns). The alignment grating was then replaced by the flight grating. The rotation of the grating and the camera focus positions were adjusted at Lyman-alpha by using motorized jigs. The final spatial and spectral resolutions were confirmed to be within the requirements.

CLASP was successfully launched on September 3rd 2015. It has been confirmed that the required image quality was kept during the flight.

9905-160, Session PS1

An optimized Fresnel array for a test space mission in UV

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The Fresnel Diffractive Imager is an optical concept dedicated to astronomy, developed by Institut de Recherche en Astrophysique et Planétologie (IRAP) in Toulouse, France. A nominal mission aims at an aperture of 6 meters for astrophysics in the Ultra-Violet, yielding an angular resolution of 0.005 arcseconds in the Lyman-? line. The feasibility of apertures up to 30 meters has been studied, yielding arc-millisecond resolutions.

Instead of a classical primary mirror to focus light, we propose a light-weight diffractive optics : the Fresnel array. This project has already proved its performances in terms of resolution and high dynamics in the laboratory, in the visible domain and at longer wavelengths. It has been successfully tested on high contrast astrophysical sources using a ground-based prototype 20cm-aperture.

Today, this project has reached the stage where a probatory mission is needed to validate its operation in space, and thus increase the Technological Readiness Level (TRL). In collaboration with institutes in Spain and Russia, we will propose this mission for the ISS with a UV astronomy program. The last progresses are a new configuration to decrease the diffusion through materials in the instrument, and the optimization of the Fresnel array. We will present that at the conference.

We have worked on improving the Fresnel array to get a better Point Spread Function (PSF) in two different ways.

First, opaque Fresnel zones were maintained with an orthogonal bars mesh, previously spaced in relation with Fresnel zones. We have shown that the PSF becomes better when bars are spaced uniformly.

Second, to further improve their performances, these optics were apodized, increasing the contrast of resulting images. More precisely, to apodize a binary mask (such as a Fresnel array) we modulate the Fresnel zones thickness from center to edge. Previously, Fresnel arrays were apodized circularly but it is more efficient when this apodization is orthogonal. We have developed a new way to apodize them.

These new improvements were tested with numerical simulations of the whole Fresnel Imager. They are leading to the production of a new array, that will be tested during a measurement campaign in order to confirm these results, before proposing it for a mission to the ISS.

9905-161, Session PS1

Development of a flight qualified 100 x 100 mm MCP UV detector using advanced cross strip anodes and associated ASIC electronics

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Photon counting microchannel plate (MCP) imagers have been the detector of choice for most UV astronomical missions over the last three decades (e.g. EUVE, FUSE, COS on Hubble etc.). Using cross strip anodes, improvements in the MCP laboratory readout technology have resulted inbetter spatial resolution (x10), temporal resolution (x 1000) and output event rate (x100), all the while operating at lower gain (x 10) resulting in lower high voltage requirements and longer MCP lifetimes.

A crossed strip anode MCP readout starts with a set of orthogonal conducting strips (e.g. 80 x 80), typically spaced at a 635 micron pitch onto which charge clouds from MCP amplified events land. Each strip has its own charge sensitive amplifier that is sampled continuously by a dedicated analog to digital (ADC) converter (ADC). All of the ADC digital output lines are fed into a field programmable gate array (FGPA) which can detect charge events landing on the strips, measure the peak amplitudes of those charge events and calculate their spatial centroid along with their time of arrival (X,Y,T) and pass this information to a downstream computer.

Laboratory versions of these electronics have demonstrated < 20 microns FWHM spatial resolution, count rates on the order of 2 MHz, and temporal resolution of ~ 1ns. In 2012 our group at U.C. Berkeley, along with our partners at the U. Hawaii, received a NASA Strategic Astrophysics Technology (SAT) grant to raise the TRL of a cross strip detector from 4 to 6 by replacing most of the19" rack mounted, high powered electronics with application specific integrated circuits (ASICs) which will lower the power, mass, and volume requirements of the detector electronics. We were also tasked to design and fabricate a "standard" 50mm square active area MCP detector incorporating these electronics that can be environmentally qualified for flight (temperature, vacuum, vibration).

The first ASICs designed for this program have been successfully fabricated and are undergoing extensive testing. We will present the latest progress on these ASIC designs and their performance and show imaging results from the 50mm XS detector using the new low power and mass ASIC electronics. We will also show our preliminary work on scaling these designs (detector and electronics) to a flight qualified 100 x 100 mm cross strip detector, which has recently been funded through another SAT grant.

9905-162, Session PS1

Ultraviolet detector with CMOS-coupled microchannel plates for future space missions

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The extreme ultraviolet (EUV) telescopes and spectrometers have been used as powerful tools in a variety of space applications, especially in planetary science. For example, an EUV telescope onboard Japan's lunar orbiter KAGUYA first took a global meridian image of the Earth's plasmasphere. In addition, the EUV spectrometer EXCEED (Extreme Ultraviolet Spectroscope for Exospheric Dynamics) onboard the Japan's small satellite SPRINT-A was launched in 2013 and it has observed tenuous gases and plasmas around the planets in the solar system (e.g., Mercury, Venus, Mars, Jupiter, and Saturn). These EUV instruments adopted microchannel plate (MCP) detection systems with resistive anode encoders (RAEs). An RAE is one of the position sensitive anodes suitable for space-based applications because of its low power, mass, and volume coupled with very high reliability. However, this detection system with RAE has limitations of resolution (up to 512 x 512 pixels) and incident count rate (up to ~104 count/sec). Concerning the future space and planetary missions, a new detector with different position sensitive system is required in order to a higher resolution and dynamic range of incident photons. One of the solutions of this issue is using a CMOS imaging sensor. The CMOS imaging sensor with high resolution and high radiation tolerance has been widely used. Here we developed a new CMOS-coupled MCP detector for future UV space and planetary missions. It consists of MCPs followed by a phosphor screen, fiber optic plate, and a windowless CMOS. We manufactured a test model of this detector and performed vibration, thermal vacuum, and performance tests. In this paper, we report the concept of this detector and initial results of our tests.

9905-163, Session PS1

Optical and structural characterization of reflective quarter wave plates for EUV range

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The knowledge of the state of polarization of the light is one of the requirements in many basic experiments in physics which is being used as a probe in the experiment. In space, polarimetry play an important role to understand the interpretation role of the coronal plasma in the energy transfer processes from the inner parts of the Sun to the outer space. Synchrotron radiation is also highly polarized, giving additional motivation to the search for a polarization analyzer. In analyzing the polarization

properties of those emission sources, the quarter wave retarder (QWR) is one of the basic tools.

In this paper a new effective multilayer design based on a combination of Aluminum with other materials have been studied to obtain a quarter wave retarder, our design approach can be used for any other angle of incidence which can work with a wider spectral range of wavelengths at lines of a particular interest in space application like Lyman series of Hydrogen (121.6 - 91.2 nm) and Oxygen VI (103.2 nm) with high, matched reflectance for both S and P polarization and at the same time a phase difference between these two states of nearly 90 degree with uncertainty ± 2 degree.

Aluminum could be a potential candidate for multilayer quarter wave retarder in the far UV range with high reflectivity because the characteristics of the Al mirror seemed to be favorable. However, aluminum mirrors tend to highly oxidize and form an Al_2O_3 layer which has very high absorption below 170 nm, reducing the reflectance of the aluminum in this region. We are making a good progress to produce and testing a new (QWRs) consisting of Al with 30 nm thickness capped with different materials that Based on preliminary theoretical results TiO_2, MgF_2, Pt and InP with different capping layer thickness ranging from 1 to 5 nm, the various samples will be prepared by the technique of electron beam evaporation and grown on Si (100) substrates, the films are deposited at a substrate temperature of 150°C with a deposition rate of 0.3 - 0.5 A/sec. The thickness of the films are designed such that to obtain a Quarter Wave Retarder working at different FUV wavelengths, and are characterized by profilometry. Selection of the working wavelength and optimization of the phase difference between s and p components is obtained by changing the angle of incidence on the sample. Reflectance measurements of the samples are performed in FUV and EUV spectral regions from 14.5 to 6 eV using synchrotron radiation at the BEAR beamline Elettra, Triest, Italy.

This system is used on the EUV reflectometer facility available in LUXOR-CNR Padova, Italy in order to realize a system to retrieve the complete state of polarization of an electromagnetic wave. The system mounts polarizer, retarder and analyzer based on the previously described design. Full characterization of the system performances will be presented.

9905-164, Session PS1

Design and improvements of the attitude control system (ACS) of the Fireball balloon experiment

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FIREBALL (the Faint Intergalactic Redshifted Emission Balloon) is a balloon-borne 1m telescope coupled to an ultraviolet fiber-fed spectrograph, designed to study the faint and diffuse emission of the intergalactic medium. The third flight of the experiment is planned in summer 2016. The goal of this paper is to describe the accurate pointing system of the 5-metre high / 1000kg gondola - that has been designed to cope with severe pointing specifications: less than 1'' in elevation and cross elevation, and about 1' around the line of sight axis, for a duration of about 1h. The pointing system is based on a multi stages - 4 DOF- closed loop system, involving an azimuth control of the gondola, a dual axis pivot assembly controlling the 1.2-meter plano siderostat, and a rotation stage that allows to control the field rotation of the instrument. The attitude measurements are given by a 3- axis gyrometer measurement, a large FOV star tracker and an accurate star camera integrated inside the instrument. The manuscript presents the design of the ACS, the limitations related to stability considerations - mainly due to of the pendulum motion and torsion modes of the flight chain-, to the actuators and sensors accuracy, and to the disturbance torques.

9905-165, Session PS1

The effects of dust outbursts on the anomalistic features observed by Rosetta Alice around 67P/Churyumov-Gerasimenko

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Beginning on August 7th of 2014, just after orbital insertion of the Rosetta spacecraft around comet 67P/Churyumov-Gerasimenko, the UV spectrometer (UVS) Alice on Rosetta began to return images containing a curved feature near the 850Å portion of the detector. This anomalistic feature (AF) was similar in appearance to a scattered light feature that had been seen before with the Lyman Alpha Mapping Project UVS on board the Lunar Reconnaissance Orbiter, as well as on Alice during the Rosetta Mars flyby, and so it initially was considered to be normal scattered light during this appearance in early August. Less than a month later, on August 29th, the feature began to quickly change in shape and intensity, earning it the nickname the ''Chameleon''. By late December 2014, the frequency of the Chameleon in science images rose to nearly 100% at comet separations less than 450 km, with the AF only disappearing in dark calibrations and 80% of stellar calibrations, causing concern among the team that it might be harming the instrument and could create problems with science analysis if it persisted. In an effort to try and determine the cause of the AF two simulations were made to model potential culprits; ions and dust particles. The ion simulations tested protons, OH^+,H_2O^+, H_3O^+, and OH^- using the SIMION program to model the interior of the Alice instrument. The dust simulation modeled the paths of charged dust particles of varying sizes, velocity vectors and charges after passing through the slit using electrostatic equations. The results found by the team indicate that the AF is most likely caused by a combination of ion and charged dust particles in the nanograin size range. The overall effect to the instrument has been in the form of a increased gain sag in the area the Chameleon most often appears in, though some exposures have to be ignored due to the Chameleon's presence and strength, which can overwhelm emission lines below the wavelength of Lyman Alpha.

9905-271, Session PS1

The HABIT (HAbitability, Brine Irradiation and Temperature) instrument for the ExoMars surface platform

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No Abstract Available

9905-21, Session 6

Analog and mixed-signal front-end ASICs for high-energy detectors in space *(Invited Paper)*

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Analog and mixed-signal front-end ASICs for high-energy detectors in space.

In most of embedded imaging systems for space applications, the increase of granularity and size of focal planes has made the use of integrated circuits almost always mandatory. To fulfill spatial and energy resolution challenging requirements these circuits have to be well suited to the sensor and to the system in terms of noise, geometry and architecture. In addition, to be accepted onboard, these electronics have to exhibit very low power consumption and must be able to survive to radiations in space. Thus, in order to be part of an optimized detection system for space, the integrated circuit has to be specifically designed for each application and becomes an Application Specific Integrated Circuits (ASIC).

The paper will focus on analog and mixed signal ASICs for spectro-imaging systems in the keV-MeV region.

It will begin with a review of the main different kinds of front-end electronic architectures:

The first task of the front-end electronics is to convert the charge coming from de detector into voltage. For most of the Silicon detectors (CCD, DEPFET, DSSD) this is done in the detector itself. For other sensor materials, charge preamplifiers operate the conversion. The paper will shortly describe the different parameters of charge preamplifiers and what drives their design.

To increase the signal to noise ratio or to reduce the duration of the signal, filtering is generally mandatory. The paper will review the main noise sources and the filtering techniques that are mostly used to reduce them.

To be space-qualified, ASICs have to be radiation hardened in terms of single event effect and total ionizing dose. The paper will shortly describe some of the typical hardening techniques.

The final noise performances of the detection systems are most often dominated by the way sensors and ASICs are connected together. The second part of the paper will take the geometry of the detector as a story line to explore different kinds of ASIC structures and architectures. From the simple mono-channel ASIC to readout CCDs to 3D ASIC prototypes to build dead-space free imaging systems, the paper will review different families of circuits for spectro-imaging systems and describe different choices that have been done all around the word for different space missions.

9905-22, Session 6

Developments in time-division, code-division, and microwave-SQUID multiplexed readout of arrays of x-ray and gamma-ray microcalorimeters

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Large arrays of cryogenic microcalorimeters are an enabling technology for x-ray and gamma-ray imaging spectrometers. For example, ESA's Athena mission will incorporate an array of ~4,000 transition-edge sensor (TES) microcalorimeters. Microcalorimeters are typically operated at temperatures near 0.1 K so multiplexed readout approaches in which one amplifier chain contains the signals from many sensors are desirable to reduce the thermal and mechanical loads on the focal plane. Successful readout schemes must preserve the exquisite energy sensitivity of cryogenic detectors. Here, we discuss recent progress developing multiplexing readout technology as part of the U.S. contribution to the Athena mission.

We are presently pursuing three multiplexing techniques for x-ray and gamma-ray microcalorimeters. First, we describe recent progress on time-division SQUID multiplexing (TDM) in which the sensor signals from a single column are sampled sequentially. This work includes efforts to increase the analog and digital bandwidth of the readout chain, to reduce cross-talk within the cryogenic SQUID circuitry, and to reduce the input noise of the readout SQUIDs. We have already demonstrated a co-added energy resolution of 2.55 +/- 0.01 eV full-width-at-half-maximum (FWHM) for 6 keV x-rays using TES detectors in a 1-column by 32-row format. Further, we anticipate presenting a new 3-column by 32-row result.

Second, we describe recent progress on code-division SQUID multiplexing (CDM). CDM shares many implementation details with TDM but CDM also eliminates the aliased SQUID noise penalty found in TDM. We anticipate presenting new CDM results in a 1-column by 32-row format. TDM and CDM are backup readout approaches for the Athena mission.

Third, we describe recent progress on microwave SQUID multiplexing (uSQUID). This readout approach provides several GHz of useful bandwidth, a roughly 100-fold increase compared to lower frequency time-, code-, and frequency-division techniques. The increased readout bandwidth provided by uSQUID readout will enable substantially higher multiplexing factors and faster sensors. We have recently completed an end-to-end demonstration of uSQUID readout using four TES gamma-ray detectors and scalable room temperature electronics based on the ROACH2 electronics. We show an average energy resolution of 47 eV FWHM at 97 keV with performance undegraded by the readout circuitry. We also describe recent work to greatly increase the number of sensors per amplifier by using the full bandwidth made available by this readout approach.

In addition to advancing the performance of multiplexing technology, we are presently building a 24-column by 40-row test platform at NIST compatible with TDM and CDM readout. The test platform will enable the characterization of TES arrays being developed at Goddard Space Flight Center for the Athena satellite mission. The test platform will also increase the readiness level of TDM and CDM readout. We will provide a status update on the assembly of this test platform. Finally, we will briefly describe the future potential of TDM, CDM, and uSQUID readout.

9905-23, Session 6

Development of x-ray microcalorimeter imaging spectrometers for the X-ray Surveyor mission concept

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While requirements for instruments on the X-ray Surveyor are still under study, an initial straw-man design includes an X-ray microcalorimeter instrument with a field-of-view of 5'x5', and pixel sizes corresponding to 1". Thus a nominal array of 300 x 300 pixels (90k pixels) on a 50 ?m pitch is required over an area of 1.5 x 1.5 cm. In general, the best energy resolution possible is desirable, however, it is considered acceptable to sacrifice some energy resolution in order to meet the rather challenging pixel number requirements.

We have developed strawman designs utilizing transition-edge sensors (TES) and magnetically coupled calorimeters (MCC) as the sensors that have the potential to meet these requirements. To reduce the number of sensors read out to a plausible scale, the most promising detector geometries are those in which a thermal sensor such a TES or MCC can read out a sub-array of 20-25 individual 1" pixels. Position discrimination is achieved through the different pulse shapes produced, since each absorber is connected by a different strength thermal connection. This "hydra" geometry is very attractive when the pixel pitch desired is this fine, and thus the combined heat capacity of the entire sub-array is therefore sufficiently small to maintain very high energy resolution. If this scale of "hydra" design is successful, then the number of sensors that are needed to be read out is the same as is currently proposed for the X-ray Integral Field Unit instrument on ESA's Athena mission (~3840). Therefore the multiplexing technologies currently being developed for Athena could be directly transferable to this spectrometer.

Alternative read-out approaches also exist that utilize dissipationless microwave SQUIDs coupled to each sensor in resonator circuits in the GHz frequency range. The resonators are spaced closely in frequency space, in principle allowing hundreds of resonators to be read out with each amplifier chain. This technology has not yet reached the same level of technical maturity. However, if successfully developed, this read-out has the potential for meeting and even exceeding the straw-man read-out requirements with just a handful of signal chains. In this presentation I will review the current state-of-the art for the detector and read-out approaches described.

9905-24, Session 6

The transition-edge EBIT microcalorimeter spectrometer

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The Transition-edge EBIT Microcalorimeter Spectrometer (TEMS) is a 1000-pixel array to be delivered to the Electron Beam Ion Trap (EBIT) facility at Lawrence Livermore National Laboratory (LLNL) in 2016. It will be the first fully operational array of its kind. TEMS will utilize the unique capabilities of the EBIT to verify and benchmark atomic theory that is critical for the analysis of data observed from the high resolution microcalorimeter spectrometers aboard the next generation of X-ray observatories such as Athena.

The TEMS detector will achieve 3 eV spectral resolution at 6 keV while being multiplexed, and will be sensitive to 0.05-10 keV. With the current generation of readout electronics, it will be able to read out 256 pixels at once. TEMS will allow count rates of up to several thousand counts per second over the entire array.

The cryogenic platform is complete and operates as expected. We have installed the wiring for all 8 multiplexer columns, along with the magnetic shielding which will shield the detectors and SQUID amplifiers from external magnetic fields and the 4T adiabatic demagnetization refrigerator magnet. The final focal plane array is nearing completion, a new 32x32 test detector array has been installed, and 1x32 and 2x16 channel columns have been demonstrated with average spectral resolution below 3.5 eV at 6 keV.

The EBIT at LLNL enables fundamental laboratory measurements that no other technique can achieve. We present some of the ongoing work with the EBIT facility measured with the EBIT Calorimeter Spectrometer (ECS), which includes benchmarking atomic theory for charge exchange, measuring absolute cross sections of the L-shell transitions for astrophysically abundant elements from Mg to Ni, and studying K-shell emission in He-like Si, S, Ar, Ni, and Fe. We also present recent laboratory spectra from TEMS and progress made in developing the focal plane assembly and cryogenic platform.

9905-25, Session 6

Toward large μ-calorimeters x-ray matrices based on metal-insulator sensors and HEMTs/SiGe cryo-electronics

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The launch of the X-ray Japanese/US mission early in 2016 with μ-calorimeters based on Metal- Insulator-Sensors (M.I.S) experiment with a 4.5eV spectral résolution, generates renewed interest on these high impedance M.I.S based on Si P:B. Starting from 2009, we are involved in a large program to build a camera consisting of a 2x2 mosaic of 32x32 pixel matrices using this sensor type. Since we rely on very similar approach of ASTRO-H design, we have concentered our efforts on the use of collective all-silicon technologies only. In the last SPIE conferences, we have presented the building block such as thermometers, sensors and cryo-electronics. Now, thanks to our new 32x32 CAD, we are today in the process of building 4 32x32 matrices per wafer. Due to our use of superconducting wiring and composite superconducting Tantalum absorber, this matrix will have a spectral resolution that should be much improved than that of ASTRO-H. Moreover, our development has a ultra low power consumption Cryo-Electronics chain, based on High Electron Mobility Transistors (HEMTs, with an AsGa/AlAsGa hetero-junction) and SiGe ASICs, that handle 34:1 multiplexing tested under cryogenic conditions. The composite Tantalum absorber have been successfully tested in 6keV X-rays, and our M.I.S. exhibit good and homogeneous sensitivity. To be compatible with the 1μW@50mK thermal budget allowed in present day spatial cryo-coolers, we have developed new thermal insulation techniques that will allow us to easily handle more than 4000 independent pixels within this limit.

9905-26, Session 6

MKIDs for x-rays: thermal kinetic inductance detectors (TKIDs)

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We will present our project to develop Thermal Kinetic Inductance Detectors (TKIDs) for the 0.5 to 20 keV band, with a projected energy resolution of 0.1 %. TKIDs are very promising detectors for X-ray imaging spectroscopy as many spectroscopic applications profit tremendously from further improving single pixel energy resolution or detector array size. Many established detector types however have started to reach their physical limits, especially when both high pixel count and high energy resolution are required. Microwave Kinetic Inductance Detectors (MKIDs) are an emerging superconducting detector technology that promises to meet that challenge: They provide an easy, passive way of multiplexing very large detector arrays while still offering high individual pixel energy resolution, single photon counting and no read noise. TKIDs modify the MKID working principle in order to detect high energy photons. In a TKID, the sensitive part of the pixel (the superconducting inductor) and a separate X-ray absorber are suspended on a freestanding membrane. TKIDs operate as microcalorimeters as they measure that membrane's temperature change after absorbing a photon. They have the potential to achieve time and energy resolutions that can compete with transition edge sensors (TESs) while avoiding their multiplexing complexity, promising a feasible way to kilo- or even mega-pixel detector arrays. This unique combination of high pixel number and energy resolution makes TKIDs ideal for X-ray astronomy and many other applications.

We will present our most recent progress with our TKID prototypes and report on fabrication and operating conditions. In 2015, our first working TKIDs showed an energy resolution of 75 eV at 5.9 keV, and we will elaborate on their dynamic range and the achieved progress in time and energy resolution. We will also compare different materials for superconductors and absorbers and explain challenges in pixel design and the data analysis necessary to extract photon energies.

9905-97, Session PS2

The design, implementation, and performance of the ASTRO-H SXS calorimeter array and anti-coincidence detector

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The calorimeter array of the Astro-H Soft X-ray Spectrometer (SXS) will provide unprecedented spectral resolution of extended cosmic x-ray sources (e.g. supernova remnants and galaxy clusters) and of all cosmic x-ray sources in the Fe-K band (around 6 keV), which will enable essential plasma diagnostics. The SXS has a square array of 36 microcalorimeters at the focal plane. These calorimeters consist of ion-implanted silicon thermistors and HgTe thermalizing x-ray absorbers. These devices have demonstrated a resolution of better than 4.5 eV at 6 keV when operated at a heat-sink temperature of 50 mK. We will discuss the basic physical parameters of this array, including the array layout, thermal conductance of the link to the heat sink, thermistor size, resistance function, absorber details, and means of attaching the absorber to the thermistor bearing element. We will present representative performance data, breaking out the contributions from other systems and from the test environment to estimate the intrinsic detector performance. A synthesized detector model will also be presented and compared to measurements.

We will also present the thermal characterization of the whole array, including thermal conductance and crosstalk measurements and the results of pulsing the frame temperature via alpha particles, heat pulses, and the environmental background.

A silicon ionization detector is located behind the calorimeter array and serves to reject events due to cosmic rays. We will briefly describe this anti-coincidence detector and its performance in conjunction with the array.

Although performance at the component level is the focus of this presentation, with system, instrument, and satellite performance to be discussed in other presentations, some in-orbit data will presented to illustrate effects at the component level.

9905-98, Session PS2

System design and implementation of the detector assembly of the Astro-H soft x-ray spectrometer

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The soft x-ray spectrometer (SXS) onboard Astro-H presents to the science community unprecedented capability (< 7 eV at 6 keV) for high resolution spectral measurements in the range of 0.5 – 12 keV to study extended celestial sources. At the heart of this SXS is the x-ray calorimeter spectrometer (XCS) where detectors (calorimeter array and anti-coincidence detector) operate at 50 mK, the bias circuit operates at nominal 1.2 K, and the first stage amplifiers operate at 130 K, all within a nominal 20 cm envelope. The design of the detector assembly in this XCS originates from Astro-E XRS and lessons learned from Astro-E and Suzaku, some of which was published in 2010 during the development of our engineering model. We have made more changes and improvements based on prototype tests since then in order to improve our flight assembly process for better reliability and overall performance. We will provide in this poster an update, present the final design and implementation of the flight detector assembly, show comparison of parameters and performance to Suzaku's XRS, and list susceptibilities to other subsystems as well as our lessons learned.

9905-99, Session PS2

Cryogen-free operation of the soft x-ray spectrometer instrument

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The Soft X-ray Spectrometer (SXS) instrument is the first space-based instrument featuring sub-Kelvin temperature control capability without the need for consumed cryogens. After the LHe supply is exhausted, cryogen-free control can continue or restart SXS operations achieving the same instrument performance. This control mode utilizes all of the SXS active cooling devices in a different arrangement. Control of three Adiabatic Demagnetization Refrigerators (ADR) stages and four active heat switches contributed by NASA, and five cryo-coolers contributed by JAXA, provide this capability. Cryo-coolers include two pairs of double-stage Stirling coolers (Shield Coolers (SC) and JT Pre-coolers (PC)), and one Joule-Thompson (JT) cooler.

The SXS Dewar Main Shell (DMS) structure suspends four interior shields and helium tank where the detectors and ADRs are mounted. The thermal stages and nominal temperatures include: Outer, Middle, and Inner Vapor Cooled Shields (OVCS, 135K; MVCS, 105K; IVCS, 35K); the JT Shield (JTS, 4.5K); helium tank, 1.525 K; and detectors, 50mK. The MVCS is thermally isolated and not controlled, but the OVCS and IVCS are cooled by the two stages of the SC, and the JTS is cooled by the JT cooler which is assisted by the PC coolers. Each cooler is voltage controlled and operates at fixed settings during cryogen-free operation.

The SXS detectors are controlled to 50mK with stability <1.0 ?K RMS for 14.3 hours by the 1st stage ADR. During this time, the 2nd stage ADR stabilizes the empty helium tank at 1.525K while the 3rd stage ADR cycles continuously every ~ 25 minutes to alternately remove heat from the 1.525K stage and transfer it to the JT cooler at ~4.5K. When the 1st stage ADR current runs out, a 2.5 hour recycle of the first two ADR stages, synchronized by the 3rd stage ADR, is performed. This process is run from the ADR Controller (ADRC) using an FPGA based state machine sequencer, repeating indefinitely and automatically.

The ADRC drives a peak of 2.0A through each ADR magnet during its recycle. The period and amplitude of current (heating) varies: the 3rd stage averages ~1A but cycles continuously with a ~25 minute period, the 2nd stage controls the helium tank using ~1A and recycles with the 1st stage which controls the detector temperature using <~0.1A and recycles every 16.8 hours. The heat from the non-superconducting portions of the magnet leads is dumped to the OVCS and IVCS representing their primary time-varying loads; the exception being orbital variation of the DMS and related effects.

Ground cryogen-free tests always began with sub-cooled shields caused by evaporating residual LHe following other tests. The time constant of the shields is about 7 days, producing a changing environment that affects the IVCS and JTS temperatures and the 3rd stage ADR period used to synchronize recycling of the other ADR stages. In lieu of very long tests, shorter tests and correlated models were used to verify the operation.

The paper describing the details of cryogen-free operation, its development and verification, will be presented on behalf of the entire SXS team.

9905-100, Session PS2

Design and on-orbit operation of the adiabatic demagnetization refrigerator on the ASTRO-H soft x-ray spectrometer instrument

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The Soft X-ray Spectrometer (SXS) on Astro-H contains a 6x6 array of x-ray microcalorimeters, which is cooled to 50 mK by an adiabatic demagnetization refrigerator (ADR). The ADR consists of three stages in order to provide stable detector cooling using either a 1.2 K superfluid helium bath or a 4.5 K Joule-Thomson (JT) cryocooler as its heat sink. If the cryogenic system performs nominally, the liquid helium will last for at least 3 years on-orbit, during which time two of the ADR's stages are used to single-shot cool the detectors while rejecting heat to the helium. After the helium is depleted, the ADR changes operating mode to cool both the helium tank (to about 1.5 K) and the detectors (to 50 mK) using the JT cryocooler as its heat sink. The Astro-H satellite completed its pre-launch environmental testing (thermal vacuum, vibration and acoustics) in September 2015, and has been shipped to Tanagashima Space Center, Japan, for launch in early 2016. This paper will discuss the basic operation of the ADR and its initial on-orbit performance.

9905-101, Session PS2

Porous plug phase separator and superfluid film flow suppression system for the soft x-ray spectrometer onboard ASTRO-H

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The sixth Japanese X-ray astronomy satellite, ASTRO-H (Takahashi et al. 2014, SPIE), carries the Soft X-ray Spectrometer (SXS, Mitsuda et al. 2014 SPIE). The SXS consists of an X-ray telescope and an X-ray microcalorimeter system operated at 50 mK. It was developed by an international collaboration lead by JAXA and NASA with European participation. The cooling chain of the SXS is composed of an adiabatic de-magnetization refrigerator (50 mK), 30 L superfluid liquid He (1.15 K), a 4He Joule-Thomson cryocooler and four 2-stage Stirling cryocoolers.

Under zero gravity, the superfluid He must be kept in the He tank. Superfluid film flow must be strictly suppressed to avoid loss of liquid. For these purposes, a porous plug phase separator and film flow suppression system is installed in the SXS dewar (Ezoe et al. 2015, Space Cryogenics Workshop[to be published in Cryogenics?]). The expected He flow rate varies from ~30 ug/s to ~3 mg/s depending on the operational case. The required film flow in the nominal operational case must be less than 2 ug/s.

The porous plug phase separator is made of porous sintered stainless steel and is installed between the dewar and the vent line. It separates vapor and liquid He using thermomechanical effect. The film flow suppression system consists of an orifice or a small diameter tube, a heat exchanger, and a pair of knife edge devices. The orifice has a small inner diameter of 1.4 mm to suppress the film flow whose flow rate is proportional to perimeter of the vent line. The heat exchanger fixed on the He tank evaporates the film flow and cools the He tank using the temperature difference between the He tank and the flowing film. The knife edge devices stop the remaining film flow by introducing atomically sharp edges into the film flow path.

Flow rate and film flow measurements have been conducted on the ground at various He temperatures from ~1.15 K to ~2.0 K, both at component level and after installing the system inside the flight dewar. For the measurements inside the flight dewar, the porous plug was wet by tilting the dewar to test the phase separation. The results meet the requirements in the various operational cases and are consistent with each other. In this presentation, we report on ground test results and in-orbit performance.

9905-102, Session PS2

The design, implementation, and performance of the Astro-H SXS aperture assembly and blocking filters

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The calorimeter array of the Astro-H Soft X-ray Spectrometer (SXS) will provide unprecedented spectral resolution of extended cosmic x-ray sources (e.g. supernova remnants and galaxy clusters) and of all cosmic x-ray sources in the Fe-K band (around 6 keV), which will enable essential plasma diagnostics. The properties that make the SXS array a powerful x-ray spectrometer also make it sensitive to photons from the entire electromagnetic band, and particles as well. (If characterized as a bolometer, it would have a noise equivalent power (NEP) of < 4 E-18 W/sqrt(Hz)). Thus it was imperative to shield the detector from thermal radiation from the instrument and optical and UV photons from the sky. Additionally, it was necessary to shield the coldest stages of the instrument from the thermal radiation emanating from the warmer stages. Both of these needs are addressed by a series of five thin-film radiation-blocking filters anchored to the nested temperature stages that block long-wavelength radiation while minimizing x-ray attenuation (subject to other design constraints). The aperture assembly is a system of barriers, baffles, filter carriers, and filter mounts that supports the filters and inhibits their potential contamination. The three warmer filters also have been equipped with thermometers and heaters for decontamination. We will present the requirements, design, implementation, and performance of the SXS aperture assembly and blocking filters.

9905-103, Session PS2

Thermal analyses for initial operations of the soft x-ray spectrometer (SXS) onboard ASTRO-H

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The Soft X-ray Spectrometer (SXS; Mitsuda et al. 2014, SPIE, 9144E, 2A) is an X-ray microcalorimeter array onboard the Japanese X-ray satellite ASTRO-H (Takahashi et al. 2014, SPIE, 9144E, 25), which is planned to be launched at the end of Japanese 2015 fiscal year. It achieves an unprecedentedly high energy resolution of <7 eV in the 0.3-10 keV band by cooling the detectors to very low temperature, ~50 mK. The instrument uses superfluid helium stored in a helium tank as a heat sink for the sub-kelvin cooler. To achieve the required hold time of 3 years, the helium tank is surrounded by multiple shields, which are cooled not only by the venting helium vapor, but also by several Stirling coolers and a Joule-Thomson cooler. The temperature of the helium is predicted to be less than ~1.2K in orbit (Fujimoto et al. 2010, SPIE, 7732E, 3H).

In the helium vent system, we employ a porous plug phase separator (Ezoe et al. 2012, Cryogenics, 52, S4-6, 178-182), which divides gas and liquid helium in zero gravity, and vents only boiloff gas. Because the porous plug functions only when the liquid helium is in the superfluid phase, the helium temperature must always be kept lower than the lambda point at ~2.17K. Hence, we need to carefully verify that the highest helium temperature in orbit, which is predicted to occur approximately 1-2 days after launch, never reaches the lambda point.

After the final topoff on the launch pad, the liquid will be pumped to low temperature (~1.3 K) with the cryocoolers operating. Leading up to launch, the pumping must be stopped so that the external plumbing can be removed. From that point, the sequence is as follows: (1) the mechanical coolers continue operating, but there is no vapor cooling of the shields, (2) within a few hours of launch, the cryocoolers are powered down, (3) after launch, opening of the vent valve begins helium vapor cooling of the shields with the coolers still off, and (4) after approximately several hours the cryocoolers are turned on. The impact of this sequence is not only warming of the liquid prior to launch, but some continued warming after launch. In order to predict the maximum helium temperature, we constructed a thermal mathematical model, which includes nodes for the helium, helium tank and the shields, and implemented effects of the helium vapor cooing and the mechanical coolers as negative heat loads at some nodes. By assuming initial temperature at each node resulted by the operation (1), we numerically simulated temperature variations of the helium, the helium tank, and the shields in the operation (2), (3), and (4). As a result, we successfully confirmed that the helium temperature can be anytime kept lower than the lambda point. In our presentation, we report the simulation results, and comparisons with actual measurements obtained in the initial operation of the SXS.

9905-104, Session PS2

Performance of the helium dewar and cryocoolers of ASTRO-H SXS

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The Soft X-ray Spectrometer (SXS) is a cryogenic high resolution X-ray spectrometer utilizing an X-ray microcalorimeter array onboard the X-ray astronomy satellite ASTRO-H, that achieves the energy resolution better than 7 eV at 6 keV in orbit. The detector array is cooled down to 50 mK using adiabatic demagnetization refrigerators (ADRs). The cooling chain from room temperature to the ADR heat-sink is composed of superfluid liquid helium, a 4He Joule-Thomson cryocooler, and 2-stage Stirling cryocoolers. It is designed to keep 30 L of liquid He for more than 3 years in the nominal case. It is also designed with redundant subsystems throughout from room temperature to the ADR heat-sink, to alleviate failure of a single cryocooler or loss of liquid helium.

The detector array, ADRs, and the aperture assembly developed by NASA were integrated, the Dewar assembly was completed in September 2014. Then thermal performance tests, function tests, and mechanical environment tests were carried out at Niihama works of Sumitomo Heavy Industries and JAXA's Tsukuba Space Center. The heat load on the helium tank was measured and it was verified that it is small enough to satisfy the lifetime requirement, in the case of nominal cryocooler operation. It was also verified that the minimum lifetime requirement can be satisfied even if one of the cryocoolers fails. The vibration isolation system against the Stirling compressors was installed during the subsystem test phase at Tsukuba Space Center, and it was verified that the detector performance satisfies the requirement. The Dewar was mounted on the spacecraft in April 2015, and have joined the a series of system-level tests (the function tests, the thermal vacuum test, and the mechanical environment test). One of the critical thermal design to use cryocoolers is the heat exhaust from them, which was verified in the system-level thermal vacuum test, when the Dewar and the cryocoolers were operated in the environment similar to that in orbit. As of December 2015, the remaining activity is the post-shipment test at the launch site (Tanegashima Space Center), and the final helium transfer and top-off operation just before the launch.

In this paper, we present the performance of the flight helium Dewar and the cryocoolers of the SXS, and initial results of the in-orbit operation.

9905-105, Session PS2

In-flight performance of pulse processing system of the ASTRO-H soft x-ray spectrometer

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The PSP (Pulse Shape Processor) is a digital signal processing electronics for the microcalorimeter instrument, SXS (Soft X-ray Spectrometer), onboard the X-ray astronomy satellite, ASTRO-H.

The SXS has 36 sensor pixels, which are operated at 50 mK to measure heat input of X-ray photons and realize energy resolution of < 7 eV FWHM in the range 0.3–12.0 keV. Receiving digitized wave-form (14 bit, 12.5 kHz sample) from 2-18 channels, two identical units of PSP-A and -B trigger X-ray events, assign an event grade, and perform optimal filtering to measure energy deposit on the microcalorimeter pixels.

We tested performance of PSP for high count rate X-ray irradiation up to ~ 2000 c/s/array on ground.

The rate of 2000 c/s/array corresponds to very bright celestial target for SXS, e.g., point-like source with X-ray flux of 1 Crab unit.

It is demonstrated that PSP can process more than ~200 events/s/array, including X-ray events and electrical crosstalk events. The electrical crosstalk events originate in wiring of the detector signal output, which have fast rise-time and easily screened out by offline processing.

We need to tune the pulse thresholds in orbit for the electrical crosstalk and possible interference with other instruments of the spacecraft.

PSP begins to discard events when the input rate exceeds the processing limit of ~200 c/s/array, namely ~50 c/s/CPU. Discarding events is usually done by flushing the waiting FIFO for each pixel.

PSP reports the time tags of the first- and last-event discarded, mixing into the normal events.

When the count rate is not uniform among the pixels, almost 100% of events are processed for pixels with count rate less than ~5 c/s/pixel, while dead time fraction increases in proportion to the count rate for pixels with higher count rate.

Non-uniform irradiation is usually the case for a point-source observation with SXS, because the X-ray from the target is focused by Soft X-ray Telescope (SXT) with half power diameter of ~ 1 arcmin, which is comparable to the SXS field of view of 3.05 arcmin. This automatic adjustment is useful for observation of bright X-ray targets, because central high rate pixels are mostly low-grade events which have degraded energy resolution, while 0outermost pixels with moderate count rate are expected to have better energy resolution.

This paper describes the results of the initial in-orbit performance of the PSP.

9905-106, Session PS2

In-flight verification of the calibration and performance of the ASTRO-H soft x-ray spectrometer

Maurice A. Leutenegger, NASA Goddard Space Flight

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The Soft X-ray Spectrometer (SXS) onboard the Astro-H orbiting x-ray observatory features an array of 36 silicon thermistor x-ray calorimeters optimized to perform high spectral resolution x-ray imaging spectroscopy of astrophysical sources in the 0.3-12 keV band. Extensive pre-flight calibration measurements are the basis for our modeling of the pulse-height-energy relation and energy resolution for each pixel and event grade, telescope collecting area, detector efficiency, and pulse arrival time. Onboard radioactive and fluorescent x-ray sources are used inflight to monitor drift in the energy scale due to variations in the thermal boundary conditions of the detectors. The energy scale is interpolated non-linearly between curves measured pre-flight at fixed reference conditions, using the reference energy from the drift monitoring. The energy scale and energy resolution are explicitly validated using observations of emission line rich sources with well-understood properties. We also characterize orbital variation in energy resolution and energy scale caused by variation in the flux of particles incident on the instrument. We use observations of broadband continuum sources and sources with constant line fluxes to validate our models of the telescope area and detector efficiency, as well as monitoring for possible contamination.

9905-107, Session PS2

First in-flight performance results of the calibration sources for the soft x-ray spectrometer instrument on ASTRO-H

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The Soft X-ray Spectrometer instrument (SXS) on the ASTRO-H satellite contains a novel type of calibration sources. These active Modulated X-ray Sources (MXS) generate electrons by means of light pulses incident on a photo cathode, which in turn are accelerated onto a target to generate a suitable X-ray spectrum.

These sources are part of the filterwheel structure.

Here we report on the first few weeks of operations of these sources and the filterwheel, in space, on board the recently launched satellite.

9905-108, Session PS2

Ground calibration of the ASTRO-H soft x-ray spectrometer

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The Soft X-ray Spectrometer (SXS) will launch aboard Astro-H in early 2016, enabling high-resolution non-dispersive spectroscopy in the soft x-ray waveband (0.3-12 keV). We present the suite of ground calibration measurements acquired from 2012 through 2015, including characterization of the detector system, anti-coincidence detector, optical blocking filters, and filter-wheel filters.

The calibration of the 36-pixel silicon thermistor microcalorimeter array includes parametrizations of the energy gain scale and line spread function for each event grade over a range of instrument operating conditions, as well as event timing and quantum efficiency data. We also describe sources of interference seen during ground testing and discuss the effects

on detector calibration.

The x-ray transmission of the set of five Al/polyimide thin-film optical blocking filters mounted inside the SXS dewar has been modeled based on measurements at synchrotron beamlines, including with high spectral resolution at the C, N, O, and Al K-edges. In addition, we present the x-ray transmission of the filters mounted on the SXS filter wheel (external to the dewar), including beryllium, polyimide contamination-blocking, and neutral density filters.

9905-109, Session PS2

Point spread function of ASTRO-H soft x-ray telescope (SXT)

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ASTRO-H satellite will be launched in February 2016. It equips two Soft X-ray Telescopes (SXTs), one of which is coupled to Soft X-ray Spectrometer (SXS) while the other is coupled to Soft X-ray Imager (SXI). Although SXTs are lightweight of ~42 kg/module and have large on-axis effective area (EA) of ~450 cm2 at 4.5 keV/module by themselves, their angular resolutions are moderate ~1.2 arcmin in half power diameter. The SXT angular resolution varies from 1.2 arcmin to 1.5 arcmin by energy to energy as well as EA. Field Of View (FOV) of SXS and SXI are considerably different, and 3.05x3.05 arcmin2 and 38x38 arcmin2, respectively, which means that characteristics important for the observation are different for the two detectors.

It is difficult that contamination amount into the SXS FOV from nearby sources through the PSF tail of SXT is evaluated with accuracy in orbit because SXS has only 6x6 pixels and SXT angular resolution is comparable to the SXS FOV. Therefore, the contamination amount was measured in the ground-based calibration at the beam line in Institute of Space and Astronautical Science. The contamination at 4.5 keV were measured with sources one width of the FOV distant from the FOV center in perpendicular and diagonal directions, that is, 3 and 4.5 arcmin off, respectively. The average EA of the contamination in the four directions with the 3 and 4.5 arcmin off were measured to be 2 and 0.6% of the SXS on-axis EA of 412 cm2, respectively. The contamination from a source two FOV widths distant, that is, 8.6 arcmin off in only one diagonal direction was also measured to be 0.1% of the on-axis at 4.5 keV.The contamination amounts were also measured at 1.5 keV and 8.0 keV at the 3 and 4.5 arcmin off in only one direction, which indicated that the fractional contamination amounts to each of the on-axis EA (535 cm2 at 1.5 keV and 340 cm2 at 8.0 keV) hardly depend on the source energy.

On the other hand, SXI FOV is wide comparing to the SXT angular resolution and it?has 1280x1280 pixels which are sufficiently fine. Therefore, the image variation associated with the off-axis and stray image arrived at SXI will be seen in orbit. The off-axis images from 4.5 to 27 arcmin in diagonal direction were acquired at intervals of 4.5 arcmin in the ground-based calibration. The image became asymmetric about normal to the off-axis direction and shrinks in that direction as the off-axis angle increased. Moreover, at off-axis angle more than 13.5 arcmin, stray clearly appeared in the off-axis direction. As for on-axis image, stray appeared at the edge of SXI of ~35 arcmin distant from the image center.

We will report the contamination from the nearby source into the SXS FOV and various off-axis images in the wide FOV of SXI.

9905-110, Session PS2

The ASTRO-H SXT performance to the large off-set angles

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The ASTRO-H, which is currently planed as launched in 2015 JFY, is the first mission to carry out high resolution spectroscopy of extended sources. The ASTRO-H's Soft X-ray Telescopes : SXT-I for a CCD camera (SXI) & SXT-S for a calorimeter (SXS), which adopt the conically approximated Wolter type-I optical system, play a role of concentrating and imaging up to ~12 keV. In this optics, X-rays usually are doubly reflected and focused by "primary" and "secondary" reflectors. However, X-rays from a large off-set angle rarely reaches the face of the detector without the normal double reflection. That is called "stray light". When we observe a target which has a large structure (like the nearby clusters of galaxies) or a faint source near a bright source, the stray lights contaminate the real signals significantly. Therefore, it is inevitable to reduce the amounts of the stray lights for the precision observations by the ASTRO-H.

Main components of the stray lights are X-rays reflected by only secondary reflectors (secondary reflection) and those reflected on the mirror substrates (backside reflection). Bare aluminum is used as the substrates. Since the critical angle of the reflection at the aluminum surface is about an order of magnitude smaller that that of the gold, the backside reflection is about one order of magnitude fainter than the secondary reflection. In order to reduce the secondary reflection, the SXTs have a "pre-collimator" (Mori et al. 2012). The pre-collimator, which is composed of cylindrical aluminum thin-foils (~120 ?m), is equipped on top of the optics so that only stray light is cut before arriving at the reflectors.

In this study, we measured the effective area of the SXTs at several off-axis angles by using the ISAS X-ray beam line (Hayashi et al. 2015) in order to estimate the level of the stray light. In particular, it is important to reveal the stray light to the SXS in order to support the high-resolution spectroscopy for diffuse X-ray emission. In the results, we found the effective area in the SXS's field of view (~3'x3') at the 30' off-axis is as small as (2.1±0.2)x10^-3 cm^2 at 1.49 keV, and those of the stray light at off-axis larger than 15' are smaller than ~10^-5 times of the effective area at on-axis (~590 cm^2). Thus, even if there is a contamination source which is 1000 times brighter than the target at 15' off-axis, we can observe less than ~ 1% contribution of the stray light with SXS. In this poster, we will also present other detail informations of the stray light of the SXTs.

9905-111, Session PS2

Reflectivity around the gold M-edges of x-ray reflector of the soft x-ray telescope onboard ASTRO-H

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The X-ray astronomy satellite ASTRO-H equips two Soft X-ray Telescopes (SXT-I and SXT-S) which cover 0.3 to ~12 keV. The SXT-I and SXT-S focuses their images on the focal plane detectors of the CCD camera (SXI) and the micro-calorimeter (SXS), respectively. A surface of an X-ray reflector of the SXTs is a gold monolayer fabricated by a replica method (Okajima et al. in this volume). The replicated method used in the SXT is a basically similar to that in the Suzaku X-Ray Telescope (XRT). Gold M absorption edges in the 2-4 keV band cause complex structures in the effective area of the SXTs. In the 2-4 keV energy band, there are emission lines from Si, Ar and S that are important in astronomy. The effective area is known as drastically changed around M-edges. Because the SXS has unprecedented high energy resolution, it is hence inevitable for making the response function of the SXTs with the fine energy pitch to quantify the reflectivity precisely around the M-edges. From Nov. 14 to Nov. 20, 2014, we measured the reflectivity around the gold M-edges in detail using the synchrotron radiation facility KEK PF BL11-B. This beamline supplies monochromatic X-rays with a double crystal monochromator with a wide energy band of the 2-4 keV band. In our experiment, Si(111) was used for the monochromating. A witness sample was used that was fabricated with the same process to those of SXT. We measured reflectivity with 2 eV energy pitch in 2100 eV to 4100 eV band including the M-I to M-V absorption edges at grazing angles of 0.5, 0.8, 1.0, 1.2, 1.4 degree around the critical angle of gold. We measured reflectivity with the finer energy pitch of the 0.25 eV in the 2200 eV to 2350 eV band included M-IV, M-V edges that were deeper absorption edges. In the reflectivity, we clearly identified the fine structures of the M-edges of the M-I to M-V. In addition, some weak but artificial structures due to the systematic errors were remained in the reflectivity those might be due to the uncontrolled beam angle and divergence into the sample. Using the measurements, we calculated atomic scattering factor f1. The f1 was determined by the curve fitting to the reflectivity at the incident angles of 0.5, 0.8, 1.0, 1.2, 1.4 degrees. Since the f1 values contains some systematic uncertainties, we also checked the residuals using the Suzaku XIS data. We found that the residuals around the M-edges to the Suzaku spectra of 4U1630-472 (BH transient) and the Crab nebula are better reduced than those with the official Suzaku response. However, there still exist small residuals around the edges. The residuals are likely originated from the systematic errors of our measurements and will be checked with the in-flight data of the ASTRO-H SXS.

9905-112, Session PS2

Reflectivity around the gold L-edges of x-ray reflector of the soft x-ray telescope onboard ASTRO-H

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Two Soft X-ray telescopes (SXT-I and SXT-S) are mounted on the ASTRO-H mission.

The SXT-I and SXT-S focuses their images on the focal plane detectors of the CCD camera (SXI) and the micro-calorimeter (SXS), respectively.

Since the incident angle to the light along the on-axis direction is at minimum 0.15 degrees, the SXT can reflect the incident X-rays above 10 keV effectively.

Although the primary energy is 6-7 keV at the Fe-K lines, this gives us a bonus of the X-ray spectroscopy above 10 keV.

The Wolter-I type optics are adopted on the SXT with a gold surface. Therefore, the effective area show the complex structures around the gold L-edges in 11-15 keV.

The optical constant of the SXT's gold surface must be measured for making the response function of these energies.

In 2014, we measured the reflectivity around the gold L-edges in detail using the synchrotron radiation facility Spring-8 BL01B1.

An Si(311) double-crystal monochromator was used for the incident beam.

An energy resolution of the beam is about 3e-5 (FWHM) which corresponds to 0.3 eV at 10 keV and 0.5 eV at 15 keV.

The second mirror is designed to focus the beam at the sample which is located at 4.9~m away. The mirrors work to focus the beam in ~0.3 mm height at the the sample.

The mirrors are tilted to cut high energy photons by tuning the tilt angle within the critical angle at the energy of ~20 keV (=3 micro rad).

A witness sample of the SXT reflector was then illuminated at the constant incident-angle at any energies in the 11--15 keV within ~0.3 mm height and~0.04~degree diverging angle with negligible higher harmonics.

Using the measurements, we calculated atomic scattering factor f1 and f2 by the curve fitting to the reflectivity at several energies.

We identified the edges associated with the L-I, II, and III transitions. We also found that the depth of these energies are roughly 60% shallower than that listed in the Henke's 1993 optical constant table.

9905-113, Session PS2

Measurements of reflectivity around the Pt L and K absorption edges of Pt/C multilayer reflector for calibration of the ASTRO-H hard x-ray telescope (HXT)

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We present the results of the reflectivity measurement of Pt/C multilayer for calibration of the ASTRO-H Hard X-ray telescope.

Japan's 6th X-ray satellite mission ASTRO-H will carry two hard X-ray telescopes (HXT) using depth-graded multilayer reflectors which provide us the capability of hard X-ray imaging observation up to 80 keV. The ASTRO-H HXT is the light-weight hard X-ray telescope using Pt/C depth-graded multilayer and high-throughput thin-foil optics. The effective area of the ASTRO-H HXT is estimated by calculation with the geometry and reflectivity of reflectors. It is difficult to calculate actual reflectivity of a multilayer reflector accurately with optical constants in literatures, because a reflectivity of a multilayer depends not only on optical constants but also on density, interfacial roughness and thickness of each layer, which are heavily dependent on a method and condition of a multilayer deposition. Furthermore, those parameters are strongly coupled to each other, thus they are hard to be determined independently. The actual reflectivity needs to be measured with the reflector fabricated by the same method and facility as that of the HXT, and then set of parameters to represent it should be derived.

For the purpose of deriving the set of parameters, reflectivity measurements of a Pt/C multilayer reflector have been done at the beamline BL01B1 of the synchrotron radiation facility SPring-8 in 2014. BL01B1 is the beamline with the bending magnet and Si Double Crystal Monochrometer which E/dE is ~ 30000 in energy range from 3.8 keV to 113 keV. The design parameters of the measured multilayer sample are the number of bilayers (N) of 15, period thickness (d) of 30 angstrom and the multilayer thickness ratio (gamma) of 0.5. The multilayer has been deposited onto the super-smooth surface of the substrate by using the fabrication facility used for reflector production of the ASTRO-H HXT. With that sample, energy scans at fixed incident angles were performed in several energy ranges; from 11.2 to 15.4 keV with 0.5 eV step including the Pt-L absorption edges, from 50 to 100 keV with 10 keV step for broad band reflectivity, from 77.5 to 80.5 keV with 0.5 keV step and from 78.1 to 78.7 keV with 0.025 keV step for detailed study of the K edge absorption feature. The reflectivity curves in the energy band of 11 to 15 keV and 50 to 100 keV including fine structures of L and K absorption edges have been obtained with high accuracy and enough energy resolution. We report the results of reflectivity measurements and the parameter set for the Pt/C multilayer reflector fabricated at the ASTRO-H HXT production facility.

9905-114, Session PS2

Ray-tracing simulation and in-orbit performance of the ASTRO-H hard x-ray telescope (HXT)

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The Hard X-ray Telescope (HXT) onboard ASTRO-H is a Wolter-I X-ray telescope utilizing Pt/C multilayer supermirrors. ASTRO-H carries two HXTs (HXT1 and HXT2), and each of them can reflect X-rays up to 80 keV onto each of the Hard X-ray Imagers (HXI). We have developed a ray-trace simulation code for the HXT. The code can take into account the tilt and twist of the mirrors, the roughness of each layer of the supermirror, and the scattering profile of each mirror. We have tuned these parameters based on the results of the characterization of HXT conducted mainly at the synchrotron facility SPring-8 Beam Line 20B2. For example, if we simulate the effective area as a function of X-ray energy with a unique roughness common to all multi-layers, the simulation tends to predict the larger effective area above 50 keV. This problem is known as a throughput problem. We have done various simulations, and found that the throughput problem can be resolved if we apply different roughness values to different mirrors; the roughness of the innermost mirror is about 10.0 A, while that of the outermost radius is about 7.0 A. So far our simulation is consistent with the measurement of the effective area within +/- 7 % in the case of the HXT1, and within +9/-3% in the case of the HXT2. The measurements of the point spread function, the half power diameter, the encircled energy function, and the vignetting function have been also compared with our simulation. We will compare the simulation with the in-flight X-ray data obtained after the launch of ASTRO-H to evaluate the in-orbit performance of the HXT. This will also clarify the effect of the launch on the status of the HXT.

9905-115, Session PS2

A laboratory test setup to study the stability of operation of the CdTe detectors within Astro-H HXI

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Astro-H is the next JAXA/NASA X-ray satellite that will be launched at the beginning of 2016.

The hard X-ray imager (HXI) is a Si/CdTe stacked detector system which is placed in the focus of a hard x-ray telescope. HXI constitute one of the four different instruments onboard Astro-H.

We are presenting the current status of a stacked detector setup which consists of two mini-HXI double sided CdTe strip detectors---similar to those used in HXI---that are read out with the low-noise readout ASIC Idef-X BD.

We describe the configuration of the setup, its spectroscopic performance, and a long-term operation of the setup.

The long-term test simulates the orbital operation of HXI using identical detector temperatures, bias voltages, and switch-on/switch-off cycles with the goal to study the detector stability and the evolution of its performance during operation.

9905-116, Session PS2

Summary of the ground-based calibration for the ASTRO-H hard x-ray telescopes (HXTs)

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ASTRO-H, the 6th Japanese X-ray satellite, equips identical two Hard X-ray Telescopes (HXTs) to carry out imaging spectroscopy in the hard X-ray energy band between 5 and 80 keV (Awaki et al. 2013). Conically-approximated thin-foil Wolter-I optical system with a focal length of 12 m is employed and Pt/C depth-graded multilayer structures are formed on the HXT mirrors in order to realize higher effective area also in the hard energy band. The HXT consists of tightly-nested 213 shells divided azimuthally into three segments and the aluminum foils with a thickness of 0.2 mm, a length of 200 mm, and a diameter of 120-450 mm are installed in the housing.

Before the launch, the HXT performance, e.g., angular resolution, effective area, vignetting function, and field of view, has been investigated extensively on ground at both SPring-8 BL20B2, 3rd generation synchrotron facility, and the X-ray pencil beam line facility of ISAS/JAXA. Consequently, angular resolutions of 1.9 and 1.8 arcmin in HPD at 30 keV are achieved for HXT-1 and HXT-2, respectively and improve up to 1.5 arcmin at 70 keV. This energy dependency in the angular resolution is explained by the difference of the waviness of the mirror reflectors. Considering the facts that the waviness of the mirror reflectors at the inner radius is smaller than that of the outer radius and high-energy photons can be reflected only at a smaller grazing angle, the angular resolution is expected to depend on energy and improve with increasing energy. The effective areas of HXT-1 and HXT-2 at 30 keV are 170 and 178 cm2, respectively. The throughput is ~0.75. The effective area decreases down to ~20 cm2 at 70 keV. The effective area as a function of an off-axis angle, i.e., the mirror vignetting function, was also measured and the resulting mirror field of views corresponding to the FWHM values in the vignetting curve are 9.9 arcmin at 8 keV and 5.6 arcmin at 50 keV. In this paper, we will report on the summary of ground-based calibration for the HXTs.

9905-117, Session PS3

Cross-calibration of the x-ray instruments onboard the Chandra, Suzaku, Swift, and XMM-Newton observatories using the SNRs 1E 0102.2-7219 and N132D

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We report on our continuing efforts to compare the absolute effective areas of the current generation of CCD instruments onboard the recently active observatories, specifically: Chandra ACIS, XMM EPIC (MOS and pn), Suzaku XIS, and Swift XRT, using 1E~0102.2-7219, the brightest supernova remnant (SNR) in the Small Magellanic Cloud, and N132D, the brightest SNR in the Large Magellanic Cloud. E0102 has strong lines of O, Ne, and Mg below 1.5 keV and little Fe emission to complicate the spectrum, while N132D has strong emission lines of Si, S, Ar, and Fe-K. The spectrum of both SNRs has been well-characterized using the RGS grating instrument on XMM and the HETG grating instrument on Chandra. We have developed empirical models that includes Gaussians for the identified lines, absorption components in the Galaxy and the MCs, and continuum components. In our E0102 fits, the model is highly constrained in that only the normalizations of the four brightest line complexes (the O VII triplet, O VIII Ly alpha line, the Ne IX triplet, and the Ne X Ly alpha) and an overall normalization are allowed to vary, while all other components are fixed. In our N132D fits, only the normalizations of the the Si XIII triplet, the S XV triplet, and the Ar XVII triplet, and an overall normalization are allowed to vary. We adopted this approach to provide a straightforward comparison of the measured line fluxes at these energies. We compare these measured line fluxes to provide an estimate of the consistency of the absolute effective area of the respective missions in the energy range from 0.5 to 3.5~keV.

9905-118, Session PS3

Evolution of temperature-dependent charge transfer inefficiency correction for ACIS on the Chandra X-ray Observatory

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As the Advanced CCD Imaging Spectrometer (ACIS) on the Chandra X-ray Observatory enters its seventeenth year of operation on orbit, it continues to perform well and produce spectacular scientific results. The response of ACIS has evolved over the lifetime of the observatory due to, among other factors, radiation damage and aging of the spacecraft. The ACIS instrument team developed a software tool which applies a correction to each X-ray event and mitigates charge transfer inefficiency and spectral resolution degradation (Grant et al. 2004). The behavior of the charge traps that cause CTI are temperature dependent, however, and warmer-than-nominal focal plane temperatures reduce the effectiveness of the correction algorithm. As the radiator surfaces on Chandra age, ACIS cooling has become less efficient at some spacecraft orientations and the focal plane temperatures can increase by a few degrees. A temperature-dependent component was added to the CTI correction algorithm in 2009. We present an evaluation of the effectiveness of this algorithm as the radiation damage and thermal environment continue to evolve and suggest updates to improve the calibration fidelity.

9905-119, Session PS3

Development of the front-end readout ASIC for charged particle counting with the RADEM instrument on the ESA JUICE mission

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This work describes the development of the front-end readout IDE3466 for RADEM on JUICE. The readout has been implemented in an application specific integrated circuit (ASIC) to meet the RADEM specifications. The ASIC has been designed for the p-side readout of silicon charged particle sensors. RADEM will use three instances of the ASIC for its protons and ions detector, its electrons detector, and its directional detector, respectively. The ASIC has 36 charge sensitive pre-amplifiers (CSA), 36 counters of 22-bits each, and one analogue output for multiplexing the pulse heights from all channels. A predecessor of the IDE3466 without counters is used in the ESA Next Generation Monitor (NGRM). The counters count pulses from charged particles in the silicon sensors depending on the charge magnitude and the programmable coincidence conditions among the 36 channels. The ASIC can be operated with an external controller for programming the ASIC registers after power-on and reading out the counter data in regular intervals. Out of the 36 channels, 32 have a high gain with saturation at 2.6 pC, and 4 have a low gain with saturation at 26 pC. The high-gain counters energy thresholds are 10-bit programmable in the range from 2.2 fC to 100 fC and also in the range from 2.2 fC to 1 pC. The low-gain counters energy thresholds are also 10-bit programmable in the range from 100 fC to 26 pC. This allows for energy binned counting of electrons from 0.3 MeV to 40 MeV, and protons from 5 MeV to 250 MeV. The ASIC operates with positive voltage supplies (+1.8V and +3.3V) and one external reference bias current. The total power consumption is less than 180 mW, depending on settings and readout rate. The ASIC has a serial peripheral interface (SPI) for programming its register settings and for the count data readout. All amplifier inputs are protected by diodes against over-voltage and electro-static discharge (ESD). The ASIC is designed in 0.35-µm CMOS process and has been manufactured at a European foundry. We have manufactured test devices and validated the design with respect to radiation. We measure a single-event-upset threshold of 50 MeVcm2/mg and we do not observe any latch-up up to the maximum tested energy of 135 MeVcm2/mg. We are currently validating the RADEM ASIC with respect to the requirements and aim for flight readiness in the year 2017.

9905-120, Session PS3

Developments in calibration of EUV and VUV detectors for solar orbiter instrumentation using synchrotron radiation

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Space-based missions exploring the spectral ranges of extreme- and vacuum-ultraviolet radiation (EUV, VUV) require on-ground at-wavelength calibration of their detectors and imaging systems to be able to provide reliable spectral intensity data. For wavelengths shorter than 200 nm monochromatized synchrotron radiation is an ideal calibration tool since it is tunable, stable in operation and inherently debris-free from its source. At the Metrology Light Source, the electron storage ring of the Physikalisch-Technische Bundesanstalt in Berlin, Germany, different beamlines cover the complete EUV and VUV spectral range for spectrally dispersed measurements. Detector systems ranging from devices like photodiodes, over imaging devices like CCD or APS to complete radiometers (or spectrometers) can be calibrated and characterized with monochromatized radiation traceable to cryogenic electrical substitution radiometers as primary detector standards. Thus it is possible to quantify the spectral responsivity (or quantum efficiency) of detectors in SI-units. Different illumination conditions are possible (e.g. beam sizes, intensities), thus allowing the determination of detector uniformity, linearity, etc. At these beamlines, also detector aging and degradation effects can be investigated. At dedicated high-flux beamlines it is possible to test up to the expected life-time dose for the devices under test.

The detector-based approach (with traceability of the radiometric quantities to a primary detector standard) is an alternative approach to the characterization of complete spectrometer systems by undispersed radiation of the storage ring, operated as a source standard. Besides our standard experimental chambers which can accommodate single detector devices, a dedicated vacuum chamber designed for instruments up to 100 kg in weight and 1.2 m length is available for instruments like, e.g., completely mounted spectrometers. The instruments are loaded into the chamber from a clean room facility which matches ISO class 5 specifications.

This chamber is capable to be used at monochromator beamlines for detector-based calibrations as well as at a beamline for undispersed radiation for source-based calibrations.

Currently the work is focused on instruments for Solar Orbiter, in particular the EUI (Extreme Ultraviolet Imager) instrument. This concerns the detector modules (for EUV as well as for Lyman-alpha), several other components (filters, mirrors) as well as the complete instrument. The full instrument calibration comes with several challenges: In contrast to the Sun, the synchrotron radiation source point is not at infinity, and the instrument's aperture is typically larger than the beam size. This applies for all imaging systems, and has to be taken into account for detector- and source based calibration procedures. Thus, precise alignment must be ensured, and measurement procedures shall include tests for angular variations as well as for non-uniform response over the entrance aperture.

We report on the current status of PTB's space instrument calibration facilities and recently developments for the radiometric characterization of components and instruments in particular for the Extreme Ultraviolet Imager (EUI) of the Solar Orbiter.

9905-121, Session PS3

Bright eruptive events polarimeter nanosatellite project: definition and performances of a spectro-imaging instrument onboard a nanosatellite payload for solar flares studies

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Nanosatellites are currently essentially aimed at training students in the frame of university projects or used as technological demonstrators. As for now, less than one fifth of the nanosatellites have a scientific interest. However, due to the standardization and miniaturization of satellite subsystems such as AOCS and RF systems (onboard X and S band antennas), the nanosatellite platforms can reach performances in terms of attitude control, pointing stability and data transfer at the level needed for scientific missions.

In this talk, we present the "Bright Eruptive Events Polarimeter" (BEEP) project that is motivated by the opportunity of having high performance

and miniaturized X-rays detectors operate on a space mission for solar studies. The properties of Caliste HD detectors (size, mass, power consumption) make these detectors a good candidate for nanosatellite missions, allowing reduced cost and development time.

The Scientific goals of the BEEP mission are to perform firstly spectroscopy and secondly polarimetry on solar flares. Even if it shall be further possible to adapt a grid to perform coded mask imaging, no imaging capabilities are required at this stage for the BEEP mission. The BEEP mission is intended to operate simultaneously as the Solar Obiter/STIX mission in order to optimize the scientific return of both instruments, benefitting from the use of the same family of detectors (Caliste) and thanks to the possibility to perform stereoscopic observations of the same events. The use of Caliste HD detectors will allow high performance photometry and spectroscopy measurements. Spectroscopy with BEEP will trigger with single hits and will cover a lower energy range (say 3-150 keV), allowing to study the transition between thermal and non-thermal emissions of solar flare events. Compton diffusion within the Caliste HD detector will allow BEEP to perform polarization measurements. Polarimetry will trigger with double hits and will be efficient for incoming photons energies greater than about 100 keV. Polarimetry without imaging will be possible only for those flares near the solar limb with a single footpoint in the field of view of the instrument.

We have defined and studied a scientific payload, based on very high performance miniaturized X-rays detectors (Caliste HD), well adapted to the observation of all kind of solar flares. We demonstrated, thanks to a system analysis, that this payload can be accommodated on a 3U CubeSat and will meet the constraints (mass, power, telemetry budgets) associated with the use of such nanosatellites.

9905-122, Session PS3

Source-based calibration of space instruments using synchrotron radiation at the metrology light source

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PTB has been involved in the calibration of many space-based instruments. The observation of solar VUV radiation is of increasing importance for various scientific questions, such as the verification of solar models, atmospheric research or space weather forecasts. These investigations often require the absolute measurement of radiometric quantities. Based on synchrotron radiation (SR), PTB can perform these absolute measurements traceable to the primary national standards. Over the past decades, PTB has performed calibrations for numerous space missions within scientific co-operations and has become an important partner for activities in this field [1].

New instrumentation in the PTB laboratory at the Metrology Light Source (MLS) has been put into operation that opens up extended calibration possibility within this context. A new facility for the calibration of radiation transfer sources in the 7 nm to 400 nm spectral range has been set-up. Also an existing VUV transfer calibration source [2] was upgraded to cover the extended spectral range from 16 nm to 350 nm.

A new large vacuum vessel is available at the MLS now, which allows the handling of complete space instruments, opening up the way for calibration of space instruments directly to the primary source standard MLS. Before its availability, the calibration of the complete space instruments was only possible by using transfer sources. These sources have been calibrated traceable to the primary source standard by PTB and have then be used at the home-institute of the corresponding cooperation partner for the calibration of the space instrument. Prominent examples for such calibrations are the calibration of transfer sources that have been used for the calibration of the CDS and SUMER spectrographs of the SOHO mission, using hallow cathode based transfer sources built and calibrated by PTB [2]. Now, also this scheme of calibration via transfer sources, which may be in some circumstances advantageous compared to the direct calibration, can be performed in-house at PTB. This respective transfer source can be rather easily recalibrated at short notice in the same laboratory at a neighbouring station, which also was put into operation recently and allows the traceable calibration of transfer sources in the spectral range from 7 nm to 400 nm [3].

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9905-123, Session PS3

The PixDD project

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The PixDD (Pixel Drift Detector) project is aimed at realizing of a fast, single-photon, pixelated focal plane detector for X-ray optics, operating in the energy range 0.5-10 keV with nearly Fano-limited energy resolution and pixel size smaller than 500 um x 500 um. The science driver is to overcome the count rate limitation related to imaging sensors (e.g., CCD) for application in X-ray astronomy and in synchrotron beamlines. The PixDD project started in early 2015 and it is being carried out in two phases. The first prototype will be a 4x4 Silicon Drift Detector with 500 um x 500 um pixels, 450 um thick. The read-out will be based on a 2D layout, where the 16 pixels will be read-out by SIRIO preamplifiers surrounding the detector. The second phase will produce a 32x32 pixel detector, 300 um x 300 um, and it will be read-out by a dedicated ASIC, developed in the context of the PixDD project, in a flip-chip configuration. In this paper we will describe the PixDD project and present its status and current results.

9905-124, Session PS3

Development of a pixelated CdTe detector module for a hard-x and gamma-ray imaging spectrometer application

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Stellar explosions are relevant and interesting astrophysical phenomena. Since long ago we have been working on the characterization of novae and supernovae in X and gamma-rays, with the use of space missions. We have been also involved in feasibility studies of future instruments in the energy range from several keV up to a few MeV, in collaboration with other

research institutes. High sensitivities are essential to perform detailed studies of cosmic explosions and cosmic accelerators, e.g., Supernovae, Classical Novae, Supernova Remnants (SNRs), Gamma-Ray Bursts (GRBs), Pulsars, Active Galactic Nuclei (AGN).

In order to fulfill the combined requirement of high detection efficiency with good spatial and energy resolution, an initial module prototype based on CdTe pixel detectors is being developed. The detector dimensions are 12.5mm x 12.5mm x 2mm and with a pixel pitch of 1mm x 1mm. Two kinds of CdTe pixel detectors with different contacts have been tested: ohmic and Schottky. Each pixel is bump bonded to a fanout board made of Sapphire substrate and routed to the corresponding input channel of the readout VATAGP7.1 ASIC, to measure pixel position and pulse height for each incident gamma-ray photon. The study is complemented by the simulation of the CdTe module performance using the GEANT 4 and MEGALIB tools, which will help us to optimize the detector design, e.g. pixel size vs angular resolution.

We will report the spectroscopy characterization of the CdTe detector module as well as the study of the charge sharing.

9905-125, Session PS3

Development of a 32-detector CdTe matrix for the SVOM ECLAIRs x/gamma camera: test results of first flight models

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ECLAIRs, a 2-D coded-mask imaging camera on-board the Sino-French SVOM space mission, will detect and locate Gamma-ray bursts (GRBs) in near real time in the 4 - 150 keV energy band. The design of ECLAIRs has been mainly driven by the objective of achieving an unprecedented low-energy threshold of 4 keV for this type of instrument. The detection plane is an assembly of 6400 Schottky CdTe semiconductor detectors of size 4x4x1 mm3 organized on elementary hybrid matrices of 4 x 8 detectors named XRDPIX, biased from -200V to -500V and operated at -20°C to minimize the leakage current and maximize the polarization time due to Schottky barrier lowering. The remarkable low-energy threshold required for the space detection plane is achieved thanks to an extensive characterization of the detectors, the development of a specific low-noise 32-channel ASIC, the realization of an innovative hybrid module composed of a thick film ceramic holding 32 CdTe detectors with their high voltage grid ("Detectors Ceramics"), associated to an HTCC ceramic housing the ASIC chip within an hermetic cavity ("ASIC Ceramics"). Finally we selected the coupling of each Detectors Ceramics with each ASIC Ceramics in order to enhance the uniformity of performance.

In this paper, we start describing the complete hybrid matrix, and then the manufacturing of a first set of 50 XRDPIX flight models (SAGEM company). Afterwards, we show tests results obtained on Detectors Ceramics, on ASIC Ceramics and on the whole modules. We analyze the different sources of noise such as design capacitances, leakage currents and ENC measurements to validate the specific technologies used for this hybridization. Then, in order to check the good pairing of each channel, we compare and confront all these values with the energy threshold and FWHM measured on spectral measurements made at the regulated temperature of -20°C in vacuum chambers by using a calibrated radioactive source of 241Am. We identify the best conditions of polarization and electronics parameters to ensure the optimum performance. We study of homogeneity of spectral properties of the 32-detector hybrid matrices and we present the ratio of more 1000 channels which could reach the key goal of a low-energy threshold of 4 keV. To finish, we conclude on the general performance required at the SVOM mission for almost a quarter of the future space camera.

9905-126, Session PS3

Directly-deposited blocking filters for high-performance silicon x-ray detectors

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Silicon X-ray detectors often require blocking filters to mitigate noise and out-of-band signal from UV and visible backgrounds. Such filters must be thin to minimize X-ray absorption, so direct deposition of filter material on the detector entrance surface is an attractive approach to fabrication of robust filters. On the other hand, the soft (E < 0.5 keV) X-ray spectral resolution of the detector is sensitive to the charge collection efficiency in the immediate vicinity of its entrance surface, so it is important that any filter layer is deposited without disturbing the electric field distribution there. We have successfully deposited aluminum blocking filters, ranging in thickness from 70 to 220nm, on high-performance CCD X-ray detectors. We report on the visible and X-ray response of filter-equipped devices.

Our methods have been used to deposit filters on the detectors of the REXIS instrument scheduled to fly on OSIRIS-ReX. REXIS has completed environmental testing and has been delivered for spacecraft integration. We discuss the current technology readiness level of this filter deposition technology.

9905-127, Session PS3

Generation of response matrix for multi-pixel CZT detectors

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Cadmium Zinc Telluride (CZT) detectors have been the workhorse in hard X-ray astronomy for a decade now, implemented in many X-ray observatories e.g. SWIFT, NuSTAR and more recently in ASTROSAT. Response matrix for CZT detectors requires precise modelling of the X-ray lines as a function of energy. Instead of showing simple Gaussian feature, these lines exhibit a long tail at lower energies because of trapping of the charge carriers due to their low mobility (μ) and lifetime (?). The effect is

found to be more significant for high energy photons as the probability of charge loss increases with the depth of interaction. Therefore, precise line modelling in case of CZT detectors needs accurate measurement of μ values for electrons and holes. For pixelated detectors, other significant components in the line modelling come from the crosstalk between the pixels due to charge sharing, fluorescence photons and Compton scattering. Charge sharing is expected to be quite significant making the CZT line profile further complicated. We have developed a numerical model taking into account all these physical processes to predict the CZT line shapes properly. The model is written in S-LANG and incorporated in spectral fitting package ISIS. Here we present the details of the numerical model and experimental measurements of mobility and lifetime of the charge carriers and the inter-pixel charge sharing fractions for 4 cm X 4 cm and 5 mm thick CZT detectors with pixel dimension of 2.5 mm X 2.5 mm, procured from Orbotech Medical Solutions (similar to the modules used in CZTI, Astrosat). In order to understand the charge sharing in the detectors in more detail, we did further experiments, results and implications of which will be discussed in this presentation.

9905-128, Session PS4

Two possible configurations of a Compton effect polarimeter for hard x-rays in the framework of the COMPASS project

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COMpton Polarimeter with Avalanche Silicon readout (COMPASS) is a research and development project that aims to measure the polarization of X-ray photons through Compton Scattering. The measurement is obtained by using a set of small rods of fast scintillation materials with both low-Z (as active scatterer) and high-Z (as absorber), all read-out with Silicon Photomultipliers. By this method we can operate scattering and absorbing elements in

coincidence, in order to reduce the background.

We are studying two configurations of satellite-borne instruments: i) a focal plane polarimeter with a single scattering element surrounded by an array of absorbers, to be coupled with a multilayer telescope for hard X-rays; ii) a large area and wide field of view polarimeter for transients and Gamma Ray Bursts composed of an array of scattering and absorbing elements, on hexagonal pattern.

In this paper we describe the two configurations of Compton Effect polarimeters and we report about the estimation of the scientific performances by means of analytical calculations and simulations.

9905-129, Session PS4

Caliste-MM: a spectro-polarimeter for soft x-ray astrophysics based on the micromegas concept

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Performing soft X-ray polarimetry in astrophysics is a topic of groing interest, giving strong information about the magnetic field of the observed sources. Only few flying experiments have been dedicated to it, and those experiments had a low sensitivity. Thanks to the development of gaseous detectors in the late 90s it became possible to use them to perform soft X-ray polarimetry, as a soft X-ray photon conversion in a gaseous detector uses the photo-electric effect : the photon is converted into a photo-electron which is ejected in a prefered azimuthal direction depending on the direction of the polarisation vector of the incident beam. By performing an histogram of the azimuthal direction of all the ejected photo-electrons, it is possible to recover the polarization direction of the source.

We used a gaseous detector based on the Micromegas concept, called the piggyback detector. Using the bulk technology, its particularity is its anode consisting only in a resistive layer spread on a ceramic plate : there are no readout electronics inside the gaseous detector, and the signal is read through the ceramic plate. Having the readout electronics outside the detector makes it easily interchangeable, and naturally protected from cosmic sparks without the need of using a protection card. The readout electronics used to read the signal must be low noise and sensitive enough to recover the signal through the ceramic, and finely pixelised to be able to recover the tracks of the photo-electrons. We decided to use the electronics called Caliste, initially developed for semi-conductor applications, but perfectly suited to read the signal of a piggyback, on top of being already space qualified.

The coupling of the piggyback detector and the Caliste readout electronics has been called Caliste-MM and various parameters, such as the gain, the influence of the distance between the ceramic and the readout electronics, or the influence of the resistivity of the detector, have been studied and modelised analytically, and the detector shows good performances. Its energy resolution in a mixture of Argon is less than 18 % FWHM at 6 keV which is the best that can be expected when using a gaseous detector based on the bulk technology : even with an outer and contactless electronics, we manage to recover the resolution of the gaseous detector alone and our device works as a spectrometer. But Argon being a high Z and high K-edge gas it is not suitable for soft X-ray polarimetry if it is used at atmospheric pressure, so it has been replaced by a mixture of Helium, and with it we are able to see good photo-electrons' tracks at 8 keV, and the reconstruction algorithm developed allows a good recovery of the ejection-direction of the photo-electrons, meaning that performing polarimetry with Caliste-MM is possible. The detector will soon be brought to a 100% polarized beam in order to measure the Q-factor of the detector, giving a last caracterization of our spectro-polarimeter with an outer and contactless electronics.

9905-130, Session PS4

Development of x-ray spectroscopic polarimetry with bent Si crystals and CFRP substrate

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The light from celestial objects includes four important quantities; images, time variation, energy spectrum, and polarization. In the field of X-ray astronomy, the capabilities of the former three have remarkably developed. On the other hand, the progress for the polarimetry is considerably delayed because of technical difficulties. In order to make a breakthrough in the field of X-ray polarimetry, we have developed a new type of optics for X-ray polarimetry. The system is collecting Bragg crystal with large area and very high sensitivity for the polarization dedicated to Fe-K lines. We adopt the 400 reflection of Si(100) crystals with high sensitivity for the polarization around Fe-K lines (6 keV), and bent the crystals with the wide X-ray band and high S/N ratio. Furthermore, to install small area of CCD to non-focal plane, it also has the spectroscopic capability with the better resolution than that of general X-ray CCD.

Our previous development was to bent Si crystals to the cylindrical shape of circle and parabola with the DLC deposition. However, for the better optics for the X-ray polarimetry, the shape should be the paraboloid of revolution to collect X-rays with high S/N ratio. We searched for the method to bent the Si crystals to the shape of the paraboloid of revolution. We devised the method to mold the crystal and the CFRP substrate?simultaneously pushed to the sophisticated foundation with the paraboloid of revolution. We developed the prototype of about 8 inch in radius of one-quater size. The crystals was also bent in the circumferential direction. Therefore, the image capability examined with optical parallel beam is 0.5 degree. In this thesis, we discussed the new design for X-ray spectroscopic polarimetry, the evaluation of image capability, and comparison of other mission.

9905-131, Session PS4

Monte Carlo study of a 3D CZT spectro-imager used as scattering polarimeter for a balloon borne experiment

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The measurement of the polarisation of the high-energy emission from cosmic sources has now become a key observational parameter for understanding the production mechanisms and the geometry of the regions involved. Therefore, a mandatory requirement for new instrumentation operating in this energy regime will be to provide high sensitivity for polarimetric measurements. In this framework, we describe the concept of a small high-performance imaging spectrometer optimized for polarimetry between 100 and 600 keV suitable for use as a stratospheric balloon-borne payload and as a pathfinder for a future satellite mission. The detector, with 3D spatial resolution, is a CZT based spectrometer in a highly segmented configuration designed to operate simultaneously as a high performance scattering polarimeter. Herein, we report on the results of a Monte Carlo study devoted to optimize the configuration of the detector for polarimetry and to evaluate the achievable performance in term of minimum detectable polarisation (MDP). In particular, we present the results for some feasible geometrical configurations (thickness and pixel/voxel scales) in presence of different background models and by using various event filters in order to maximize the MDP. Furthermore, to assess the reliability of the implemented numerical model, we compare Monte Carlo results with experimental data obtained with the high performance CZT spectro-imager module Caliste.

9905-132, Session PS4

Performances of the gas pixel detector: an x-ray imaging polarimeter for upcoming missions of astrophysics

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The Gas Pixel Detector allows for making imaging X-ray polarimetry resolved in energy and time in the classical energy band for X-ray Astronomy. It is already built in a configuration suitable for flight and in this paper we present its main characteristics, including a measurement of stability in almost three years of operation, for both the energy resolution and the modulation factor. We also show energy dependent position resolution, modulation factor and energy resolution all obtained at the calibration and test facility at IAPS-INAF. The results of these measurements show that the performances are such to fulfill already the requirements for XIPE, a mission under study for ESA M4 and for IXPE a mission in phase A for NASA/SMEX.

9905-133, Session PS4

The on-board calibration system of XIPE

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The calibration system for XIPE is aimed at providing a way to check and correct possible variations of performances of the Gas Pixel Detector during the three years of operation in orbit, while facilitating the observation of the celestial sources. This will be performed by using a filter wheel with a large heritage having a set of positions for the calibration and the observation system. In particular it will allow for correcting possible gain variation, for measuring the modulation factor using a polarized source, for removing non interesting bright sources in the field of view and for observing very bright celestial sources. The on-board calibration system is composed of three filter wheels, one for each detector and it is expected to operate for a small number of times during the year. Moreover, since it operates once at a time, within the observation mode, it allows for simultaneous calibration and acquisition from celestial sources. In this paper we present the scope and the requirements of the on-board calibration system, its design, and a description of its possible use in space.

9905-270, Session PS4

Geometrical tools for the analysis of x-ray polarimetric signals

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No Abstract Available

9905-27, Session 7

The ASTRO-H x-ray astronomy satellite

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ASTRO-H, the new Japanese X-ray Astronomy Satellite following Suzaku, is an international X-ray mission, planed for launch in Feb, 2016. ASTRO-H is a combination of wide band X-ray spectroscopy (3 - 80 keV) provided by focusing hard X-ray mirrors and hard X-ray imaging detectors, and high energy-resolution soft X-ray spectroscopy (0.3 - 10 keV) provided by thin-foil X-ray optics and a micro-calorimeter array. The mission will also carry an X-ray CCD camera as a focal plane detector for a soft X-ray telescope and a non-focusing soft gamma-ray detector based on a narrow-FOV semiconductor Compton Camera. With these instruments, ASTRO-H covers very wide energy range from 0.3 keV to 600 keV. The simultaneous broad band pass, coupled with high spectral resolution of <7 eV by the micro-calorimeter will enable a wide variety of important science themes to be pursued. The ASTRO-H mission objectives are to study the evolution of yet-unknown obscured super massive Black Holes in Active Galactic Nuclei; trace the growth history of the largest structures in the Universe; provide insights into the behavior of material in extreme gravitational fields; trace particle acceleration structures in clusters of galaxies and SNRs; and investigate the detailed physics of jets. In this presentation, we will describe the mission, scientific goal and report the initial performance on the orbit.

9905-28, Session 7

The ASTRO-H high-resolution soft x-ray spectrometer

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We describe the overall design and performance of the Soft X-Ray Spectrometer (SXS) for the JAXA Astro-H mission, to be launched in February 2016. The instrument is based on a 36-pixel array of semiconductor microcalorimeters designed for high resolution over the 0.3-12 keV energy band at the focus of a high throughput, grazing-incidence x-ray mirror. The instrument was designed to provide high-resolution, non-dispersive spectroscopy over a large simultaneous bandpass, and is a joint collaboration between the JAXA Institute of Space and Astronautical Science and many partners in Japan, and the NASA/Goddard Space Flight Center and collaborators in the US. The principal components of the spectrometer are the microcalorimeter detector system, a low-temperature anticoincidence detector, a 3-stage adiabatic demagnetization refrigerator (ADR) to maintain 50 mK operation under both cryogen and cryogen-free operation, a hybrid liquid helium/cryogen-free dewar with both Stirling and Joule Thomson coolers, and electronics for reading out the array, processing the x-ray data for spectroscopy, and operating the ADR and cryocoolers. The dewar is closed out by a complex aperture system that has five thin-film filters designed to provide high x-ray transmission with low heat loads to the dewar and detector system, and prevent contamination from condensing on the filters.

The instrument was designed to have better than 7 eV energy resolution, and was demonstrated to achieve 4-5 eV resolution across the array at the full level of spacecraft integration during extensive ground testing prior to launch. The overall cooling chain was designed to provide a lifetime of at least 3 years in orbit, and continue to operate without liquid helium to provide redundancy and the longest operational lifetime for the instrument. The instrument was tested in both modes prior to launch, and provides about 43 hours of hold time at 50 mK in cryogen mode (1.2K He temperature) with a 45 min recycle time, and about 14.7 hours at 50 mK in cryogen-free mode with a 2.5 hour recycle time (He tank maintained at 1.525K by the third stage ADR).

Among the many challenges for the instrument is maintaining an end-end knowledge of the absolute energy scale of the instrument to better than 2 eV. This has been done on the ground using an extensive series of calibration measurements over a very wide energy range, and at multiple array temperatures. The in-flight energy scale is maintained using controllable x-ray sources mounted just above the entrance to the dewar aperture that can be used simultaneously with celestial observations.

In this presentation, we will describe the SXS instrument and cover its main design elements, and give an overview of the ground and early in-flight performance.

This presentation is being given on behalf of the very large international team that developed this complex instrument.

9905-29, Session 7

In-flight performance of the soft x-ray spectrometer detector system on ASTRO-H

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The SXS instrument will be launched aboard the Astro-H observatory in early February, 2016. The SXS spectrometer is based on a high sensitivity x-ray calorimeter detector system that has been successfully deployed in many ground and sub-orbital spectrometers. However, the SXS will be the first long-term implementation in space. The instrument will provide essential diagnostics for nearly every class of x-ray emitting objects from the atmosphere of Venus to the outskirts of galaxy clusters, without degradation for spatially extended objects. The SXS detector system consists of a 36 pixel cryogenic microcalorimeter array operated at a heat sink temperature of 50mK. In pre-flight testing, the detector system demonstrated a resolving power of better than 1300 at 6 keV with a simultaneous bandpass from below 0.3 keV to above 12 keV with a timing precision below 100 us. In addition, a solid stage anti-coincidence detector is placed directly behind the detector array for background suppression. The detector error budget includes the measured interference from the SXS cooling system and the spacecraft. Additional margin for on-orbit gain-stability, and on-orbit spacecraft interference are also included in the error budget predicting an on-orbit performance that meets or exceeds the 7 eV FWHM at 6 keV requirement. Here we discuss the actual on-orbit performance of the SXS detector system and compare this to performance in pre-flight testing and the on-orbit predictions. We will also discuss the on-orbit gain stability, any additional on-orbit interference, and early measurements of the on-orbit background.

9905-30, Session 7

Vibration isolation system for cryocoolers of xoft x-ray spectrometer onboard ASTRO-H

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The design and performance of vibration isolation system used for Soft Soft X-ray Spectrometer (SXS) onboard Astro-H will be presented. SXS onboard Astro-H is a microcalorimeter-type spectrometer. A microcalorimeter is a thermometer-based detector, measuring X-ray energy of a X-ray photon as temperature increase by each X-ray photon input. SXS detector is installed in a dewar and cooled at 50~mK to have a good sensitivity in measuring temperature increase with high resolution. It is also sensitive to any other energy input, including micro-vibration. This kind of stray energy input could increase the noise of the detector and cause gain variation, both of which could significantly degrade the energy resolution of the detector. The energy resulution of the SXS engineering model indeed suffered from micro-vibration from cryocoolers (two-stage Stirling coolers) used for cooling the dewar. The microvibration in the frequency of several hundred Hz was transmitted to inside the dewar, stimulating the vibration of detector cold stage, and inducing a variable heat input on to the detector heat sink. This variation in heat load caused significant gain variation of the detector, resulting in unacceptable degradation in energy reslution; five times worse than the requirement. This influence of microvibration was mitigated in flight model program, by introducing vibration isolation system between the cryocoolers and the dewar. The vibration isolation system consists of flexure springs that isolates the vibration from cryocoolers, bumpers that restricts the displacement by mechanical load at launch, and thermal straps that compensates the reduced thermal connection between each cryocooler and the dewar by introducing the vibration isolation system. The vibration isolation system was carefully designed to achieve two conflicting requirements: to have small transmissibility for microvibration in several hundred Hz range, requiring low natural frequency of the flexure, and to avoid too large amplification for launch vibration, requiring not-too-low natural frequency. The detector performance with the vibration isolation system was verified in both ambient condition and thermal-vac condition, showing no detectrable degradation in energy resolution.

9905-31, Session 7

In-orbit operation of the ASTRO-H SXS

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ASTRO-H is an X-ray observatory scheduled to be launched in Feb 2016. The soft X-ray spectrometer (SXS) onbaord the satellite is one of the payloads using an X-ray calorimeter array at a focus of X-ray telescope. SXS has an unprecedented spectroscopic performance particularly in the about 2-15 keV band. The sensor working temperature is controlled at 50 mK by a multiple cooling chain using adiabatic demagnetization refrigerators, mechanical cryo-coolers, and liquid He.

SXS is a cold-launch system, which is launched without power. However, it is powered just before launch and soon after launch to prevent warm-up of the system and immediate He venting in the orbit. A series of time-critical operations is planned in the first few weeks for the first light as early as possible. In this presentation, we summarize the result of the in-orbit operation covering from the launch to the transition to the normal observing operation.

9905-32, Session 7

First peek of ASTRO-H soft x-ray telescope (SXT) in-orbit performance

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ASTRO-H is a Japanese X-ray astrophysics satellite under the development led by Japan and US. It has been completed and is scheduled to be launched in February, 2016, from Tanegashima, Japan by a JAXA H-IIA launch vehicle. It has two Soft X-ray Telescopes (SXTs), among other instruments, that were developed by NASA's Goddard Space Flight Center. One is for an X-ray micro-calorimeter instrument and the other for an X-ray CCD camera, both covering the X-ray energy band up to ~15 keV. The SXT employs a conically approximated Wolter I grazing incidence optic with 203 nested shells. The SXT design builds on the legacy of Suzaku mirrors and has a focal length of 5.6 m and a diameter of 45 cm. Each shell is segmented and its gold reflecting surface is replicated from a Pyrex glass tube onto a 0.15-0.3 mm thick shell substrate with an epoxy buffer layer.

The two flight SXTs have been completed and delivered to ISAS/JAXA in Japan for full X-ray characterization at their X-ray beamline, and then transported to JAXA Tsukuba Space Center for the spacecraft integration. The SXT has been successfully installed and aligned to the spacecraft observing axis as well as the calorimeter/CCD instrument. The SXT performance, such as on/off-axis effective area, on/off-axis point spread function (PSF) was measured on ground. Amount of the stray light from off-axis angles was also measured.

Furthermore, local effective area and PSF across the mirror were measured in order to optimize a ray-tracing simulator to reproduce the SXT performance as well as possible, which will be used to generate a SXT response for astronomical observations. According to the ground calibration, the on-axis angular resolution is about 1.2 arcmin (HPD), independent of energy, and the on-axis effective area is about 590 and 380 cm^2 at 1.5 and 8 keV, respectively, yet the SXT weighs only 42 kg. The amount of the stray light is found to be much less than that of the Suzaku telescope. All the measured performance met the project requirement and actually exceeded the goal in the original proposal. In this paper, we will present the overview of the SXT design as well as the in-flight SXT performance for the first time, by comparing with the ground calibration results and the ray-tracing simulations, particularly the PSF and the end-end effective area for the calorimeter and the CCD instrument. Due to the extremely high energy resolution of the calorimeter system (~5 eV), a prominent feature may be seen in a observed spectrum around the gold M and L absorption edges. We will also discuss such a feature by comparing with ground measurement results of individual reflectors obtained at a synchrotron facility.

9905-33, Session 8

Soft x-ray imager (SXI) onboard ASTRO-H

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We have developed an X-ray CCD camera, the Soft X-ray Imager (SXI) onboard the ASTRO-H satellite. The SXI consists of 4 CCDs with an effective area of 60mm square. The CCD is a P-channel type, back-illumination, resulting in a depletion layer of 200um. The physical pixel size is 24um square while we will run the SXI in 2x2 pixel binning mode that allows us to employ a similar method for event detection to those developed for ASCA and Suzaku. Since we demonstrated the validation of the artificial charge injection on the CCD against the CTI degradation in space, we apply it to the SXI from the beginning of the mission. We have designed the surrounding electronics for the CCD based on those developed for ASCA and Suzaku. We introduce an analog ASIC in the front-end electronics so that we can reduce the weight, size and power. We employ two mechanical coolers to cool CCDs around -110C. We can cool CCDs more in case that we notice a degradation of the CCDs due to the radiation damage.

There are two types of soft X-ray detectors onboard ASTRO-H: SXI and an X-ray calorimeter (SXS). Both of them are placed at the focal plane for individual soft X-ray telescope (SXT) that are looking at the same direction. The SXI has a large field of view (FOV, 38' square), ten times larger than that of the SXS although the SXS has an excellent energy resolution. Therefore, we can obtain a detailed spectrum at the aim point by the SXS and an image around it by the SXI. The SXI covers the energy range from 0.4keV to 12keV. There are a few absorbing materials above the CCD: a thermal shield of the SXT, a contamination blocking filter for the SXI and a SiO_2 layer on the CCD. They determine the low energy end of the SXI. The high energy end is limited by the SXT.

ASTRO-H passed the final review at the end of 2015 and will be launched in the beginning of 2016. It will be commissioned soon after the initial check-out phase. In the SPIE symposium, we will be able to report the first light of the SXI. Based on the previous satellites, we notice that there are some ambiguities in the CCD spectrum due to its insufficient energy resolution. Sometimes, we have to add an extra emission line around 1.2keV that must come from Fe-L transitions. We do not know how much fraction below 1keV is contributed by the continuum component since there are so many emission lines clustered there in thin thermal plasma. By combining the SXI and SXS results, we will be able to practically demonstrate what generates the CCD spectrum. We expect that this knowledge will help us to know the detailed spectrum whole through the entire FOV of the SXI.

9905-34, Session 8

The hard x-ray imager (HXI) onboard ASTRO-H

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ASTROH is the sixth of a series of Japanese X-ray astronomy satellite, to be launched into orbit in early 2016. The 2.5 t large mission is designed for; (1) high-resolution soft X-ray spectroscopy (at 0.3-12 keV), with resolving power >1000 at 6 keV using X-ray micro-calorie-meter (SXS) coupled with a soft X-ray telescope (SXT), and (2) wide-band coverage up to 600 keV. Among them, 5—80 keV imaging spectroscopy is achieved with the hard X-ray imaging spectrometers (HXIs) coupled with hard X-ray telescopes (HXTs), with angular resolution of 2' half-power diameter (HPD). Soft energy band is covered with a X-ray CCD (SXI) coupled with another SXT, and two soft gamma-ray detectors (SGDs, non-imaging) cover up to 600 keV.

The hard X-ray imager (HXI) is located at the bottom of the satellite, at the 12 m long focal position of the HXT. ASTRO-H carries 2 set of this system, providing in total of 300 cm2 effective area at 30 keV. It has a field-of-view 9'.2x9'.2 wide and are designed to detect sources as dim as a few times 1/1000,000 of the Crab nebula. To obtain a good overlap with the SXI (working up to 12 keV) and also cover the Fe-K line complex, it is required to able to observe down to 5 keV.

The HXI imager is made of 5 layers of semiconductor double-sided strip detectors (DSDs); 4 layers of Si (DSSDs) at the top, and a CdTe layer (CdTe-DSD) at the bottom. The strip pitch is 250 um, covering 3.2x3.2 cm2 area with 128x128 strips orthogonally oriented in the cathode and anode sides. In total 1280 ch of signals are read-out via specially designed analog ASICs, VA32TAs, featuring low power and good energy resolution of 1 keV (full width at half maximum; FWHM) for the DSSDs and 2 keV for the CdTe-DSD.

The semiconductor imagers are covered almost in 4-pi direction with ~3 cm thick BGO scintillators. There are 9 BGO units all read out via avalanche photo-diode to provide anti-coincidence signal to the imager, in order to reduce in-orbit background signals generated from cosmic and albedo X-rays, as well as cosmic-rays protons and material activations from them.

Flight model detectors of the HXI was manufactured in 2014, and mounted, integrated and tested on the satellite throughout 2015. The system successfully went through all the mechanical, thermal and electrical tests. The energy resolution, lower threshold, and low background were verified to meet the requirement, and all system is ready for launch. After the launch, the satellite will be activated gradually. The extendable optical bench equipped at the HXI-mounted plate will be deployed by ~6 m long prior to the HXI power on. Then, all the operation parameters and bias will be applied for actual observations of high-energy celestial targets, the first lights and continue observations afterwards.

9905-35, Session 8

Performance of ASTRO-H hard x-ray telescope (HXT)

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The Japanese X-ray Astronomy Satellite, ASTRO-H carries hard X-ray imaging system, covering the energy band from 5 keV to 80 keV.

The hard X-ray imaging system consists of two hard X-ray telescopes (HXT) and the focal plane detectors (HXI). The HXT employs tightly-nested, conically-approximated thin foil Wolter-I optics. The mirror surfaces of HXT are coated with Pt/C depth-graded multilayers.

We carried out ground calibrations of HXTs at the synchrotron radiation facility SPring-8/ BL20B2 Japan, and found that total effective area of two HXTs was about 350 cm2 at 30 keV, and the half power diameter of HXT was about 1.9 arcmin. The calibration data on ground is used to make parameter files of the raytrace program which simulates the X-ray performance of XRTs onboard ASTRO-H. The pre-launch parameters files are going to be archived in the ASTRO-H calibration database. We will perform in-flight calibrations of HXTs in order to perform a fine tuning of the parameter files.

9905-36, Session 8

The soft gamma-ray detector (SGD) onboard ASTRO-H

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ASTRO-H is the next generation X-ray satellite in Japan, and intended to carry instruments with broad energy coverage and exquisite energy resolution. The Soft Gamma-ray Detector (SGD) is one of ASTRO-H instruments and will feature wide energy band (60--600 keV) with a lower background level by a factor of 10 than the past observatories. The SGD achieves low background by combining two technologies; a Compton camera scheme where Compton kinematics is utilized to reject backgrounds and a narrow field-of-view active shield which was realized by the Suzaku HXD. The Compton camera in the SGD is realized as a hybrid semiconductor detector system which consists of silicon and CdTe (cadmium telluride) sensors. Good energy resolution of semiconductor sensors and readout ASICs leads to a good background rejection capability with better constraints on Compton kinematics. Utilization of Compton kinematics also enable the SGD to measure the gamma-ray polarization, opening up a new window to study cosmic gamma-ray emission processes. In this paper, we will present the evaluation test results of the flight model during the ground calibration test and the final thermal vacuum test. Moreover, we will also present the on-orbit observation results.

9905-37, Session 8

ASTRO-H data analysis, processing, and archive

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Astro-H is the next major international X-ray/Gamma-ray mission set to launch in February 2016. The complex payload consists of four different types of instruments (SXS, SXI, HXI and SGD) that operate simultaneously and provide data in the 0.3 keV- 600 keV energy band. After an initial PV phase, Astro-H operates as an observatory with time open to the astronomy community via competitive proposals. This paper presents the analysis software created to calibrate and analyze the data along with the plan for the archive and user support. This has been a collaborative effort shared between scientists and software engineers working in Japan and USA.

Data are translated in FITS event format, directly from the telemetry. The software, built under the FTOOLs environment, operates directly on the event FITS files and calibrates the time, energy and coordinate domains using calibration information stored in an external calibration database (CALDB). The calibration database is updated throughout the mission to account variation of the instruments performance. The software has been trained with data taken during the integration and test of satellite.

A common approach across the instruments has been used to assign time and coordinate information and a new ray-tracing code can model both the low energy telescopes used in conjunction with the SXS and SXI instruments as well as the high-energy telescope used in conjunction with the HXI. Many of the existing general FTOOLs are used via scripts to extract source light curve, images and spectrum. The package also includes a new graphical user interface aimed to help in the energy line recognition detected by the calorimeter instrument, SXS, as well as a simulator for proposal preparation that may be used in conjunction with the ray-tracing.

The software is distributed to the community via the HEASARC, together with CALDB, and it is also integrated in the processing pipeline. The products of the processing pipeline are calibrated events as well as 'filtered' data and high level products. The Astro-H data, outputs of the pipeline processing, are archived both in Japan and USA.

9905-38, Session 9

XIPE: the x-ray imaging polarimetry explorer

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XIPE the X-ray Imaging Polarimetry Explorer has been selected for Study Phase for ESA M4 along with other two missions operating in very different fields. It is expected to re-open the window of X-ray polarimetry after 40 years from the last positive measurement of the Crab Nebula made by OSO-8 by means of Bragg diffraction, but now exploiting the photoelectric effect in gas. Its payload consists of only three Gas Pixel Detectors at the focus of three large area, low weight but having a good angular resolution, electroformed mirror shells.

Now, thanks to its moderate resources, it will be possible to measure X-ray polarization in hundreds of sources for studying in a novel way almost all the classes in high energy Astrophysics, since they are polarized at least as at some extent. XIPE is supposed to operate for three years. 75 % of the data will be available worldwide, through a competitive Guest Observer program, while the remaining 25 % will be exploited from the team, as core program to guarantee its minimum science return. All data will be made public after one year.

9905-39, Session 9

The polarimeter for relativistic astrophysical x-ray sources

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The Polarimeter for Relativistic Astrophysical X-ray Sources (PRAXyS) is one of three Small Explorer (SMEX) missions selected by NASA for Phase A study, with a launch date in 2020. The PRAXyS Observatory exploits grazing incidence X-ray mirrors and Time Projection Chamber Polarimeters capable of measuring the linear polarization of cosmic X-ray sources in the 2-10 keV band. PRAXyS combines well characterized instruments with spacecraft rotation to ensure low systematic errors. The PRAXyS payload is developed at the Goddard Space Flight Center with readout components from the JHU Applied Physics Laboratory and JAXA. The LeoStar-2 spacecraft bus is developed by Orbital ATK, which also supplies the extendable optical bench that enables the Observatory to be compatible with a Pegasus class launch vehicle.

A nine month primary mission will provide sensitive observations of multiple black hole and neutron star sources where theory predicts polarization is a strong diagnostic as well as exploratory observations of other high energy sources. The PRAXyS team is committed to releasing the primary mission data to the community rapidly as well as to vigorous support for a Guest Observer driven extended mission.

9905-40, Session 9

The Imaging X-ray Polarimetry Explorer (IXPE)

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IXPE is a mission undergoing a Phase-A study as a possible NASA Small Explorer. IXPE uses X-ray polarimetry to expand dramatically observation space and to provide new input to our understanding as to how X-ray emission is produced in objects where physics under extreme conditions dominates: neutron stars, pulsar wind nebulae, and stellar and supermassive black holes. The mission is very low-risk, making use of mature flight elements combined in a system with conservative resource margins and run by a team with extensive mission experience, in X-ray astronomy, especially X-ray polarimetry. Not only will the mission expand observation space by adding both degree of polarization and position angle to the list of observational parameters, it will also add imaging capability in a significant number of important contexts such as jets in active galaxies. The mission combine 30-arcseond half-power-diameter optics with high precision gas pixel detectors whose two-dimensional symmetry is devoid of any significant systematic effects.

9905-41, Session 9

Opening the field of soft x-ray polarimetry

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We present continued development of a telescope for measuring linear X-ray polarization over the 0.2-0.8 keV band. We employ multilayer-coated mirrors as Bragg reflectors at the Brewster angle. By matching to the dispersion of a spectrometer, one may take advantage of high multilayer reflectivities and achieve polarization modulation factors over 95%. We have constructed a source of polarized X-rays that operates at a wide range of energies with a selectable polarization angle. We will present results from measurements of new laterally graded multilayer mirrors and new gratings essential to the design. Finally, we will present a design for a small telescope for suborbital or orbital missions. A suborbital mission could measure the polarization of a blazar such as Mk 421 to 5-10 percent while an orbital version could measure the polarizations of neutron stars, active galactic nuclei, and blazars.

Support for this work was provided by the National Aeronautics and Space Administration through grant NNX15AL14G and by Research Investment Grants from the MIT Kavli Institute.

9905-42, Session 9

POLIX: a Thomson x-ray polarimeter

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POLIX is a medium energy Thomson X-ray polarimeter for a small astronomy satellite of ISRO. It uses a collimator, a scatterer and a set proportional counters to detect the scattered X-rays. This instrument will provide unprecedented opportunity to measure X-ray polarisation in the energy range of 5-30 keV in a large number of sources of different classes with a minimum detectable linear polarisation degree of 2-3%. The prime objects for observation with this instrument are the bright X-ray sources: accretion powered neutron stars, accreting black holes in different spectral states, rotation powered pulsars, magnetars, and active galactic nuclei. We will describe the design details of POLIX and its sensitivity for polarization measurement of cosmic X-ray sources.

9905-43, Session 9

Hard x-ray imaging polarimeters for Polaris

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Hard X-ray polarimetry is complementary to the soft X-ray polarimetery, such as planned with PRAXyS, IXPE, XIPE. Although the number of hard X-ray photons is not larger than in the soft X-ray regime, polarization degrees are in general expected to be higher than in the soft X-ray band. This is due to the fact that non thermal radiation is prominent in the hard X-ray band. For example, reflection component from the accretion

disks around black holes, which should have high polarization degree, is dominant in the hard X-ray band.

We thus plan hard X-ray polarmetry mission, PolariS, for a small satellite. Its target is tens of sources brighter than 1/100 Crab. It would employ three modules of hard X-ray mirrors and scattering type imaging polarimeters installed on their focal plane.

We show the current status of the PolariS mission, and recent development of the imaging polarimeters.

The imaging polarimeter consists of two kinds of scintillator pillars and multi anodes photomultiplier tubes (MAPMT). Incident position and scattered direction is measured with this system. We have already built bread board models of the PolariS imaging polarimeter in which 50% of the surrounding unit to catch scattered X-rays are employed. We performed X-ray irradiation tests at a synchrotron facility. We confirmed the system has polarization sensitivity with as modulation factor M of 0.5-0.6 to 10-80keV X-rays. The detection efficiency is higher than 1% at 20keV, and about 20% at 80keV. The efficiency would be doubled if we employ full coverage of the surround units. We are also optimizing data processing techniques to gain high efficient for low energy incidence.

9905-44, Session 9

The x-ray polarimeter instrument on board the Polarimeter for Relativistic Astrophysical X-ray Sources (PRAXyS) mission

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The Polarimeter for Relativistic Astrophysical X-ray Sources (PRAXyS) is one of three Small Explorer (SMEX) missions selected by NASA for Phase A study. The PRAXyS observatory carries an X-ray Polarimeter Instrument (XPI) capable of measuring the linear polarization from a variety of high energy sources, including black holes, neutron stars, and supernova remnants.

The XPI is comprised of two identical mirror-Time Projection Chamber polarimeter telescopes with effective area TBD at 3 keV, capable of photon limited observations for sources as faint as 1 mCrab. The XPI is built with well-established technologies. This paper will describe the performance of the XPI flight mirror and the protoflight polarimeter.

9905-45, Session 10

Large area x-ray proportional counter (LAXPC) instrument onboard ASTROSAT

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ASTROSAT India's first dedicated astronomy space mission was launched on September 28, 2015. The Large Area X-ray Proportional Counter (LAXPC) is one of the major payloads on ASTROSAT. A cluster of three co-aligned identical LAXPC detectors provides large area of collection of about 8000 cm2.. The large detection volume (15 cm depth) filled with mixture of xenon gas (90(%) and methane (10%) at ~ 2 atmospheres pressure, results in detection efficiency greater than 50%, above 30 keV. The LAXPC instrument is best suited for X-ray timing and spectral studies over energy range of 3-80 keV. It will provide the largest effective area among all the satellite missions flown so far worldwide and will remain so during next 5-10 years for X-ray studies in the given energy range. The LAXPC detectors have been calibrated using radioactive sources in the lab. GEANT4 simulation for LAXPC detectors was carried out to understand detector background and its response. The LAXPC instrument became fully operational on 19th October 2015 for the first time in space. We have performed detector calibration in orbit. The LAXPC instrument is functioning well and has achieved all detector parameters proposed initially. In this paper, we will describe LAXPC detector calibration in lab as well as in orbit along with first results.

9905-46, Session 10

In-orbit performance of SXT aboard AstroSat

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A soft X-ray Imaging Telescope (SXT) built in India was launched in a near Earth near equatorial orbit aboard the AstroSat on September 28th, 2015. The X-ray optics was built in the Tata Institute of Fundamental Research, India and mated to a Focal Plane camera containing a cooled CCD built in collaboration with the Space Research Centre of the University of Leicester, UK. The electronics for the camera including the temperature control, telemetry and telecommand system for various modes of operation was also built in-house in TIFR, and it was switched on within 3 days of the launch. The first light with SXT was seen on October 26th, 2015 after a sequence of operations. Several cosmic targets have been observed since then during the Performance Verification phase lasting until March 31, 2016. A few near-simultaneous observations have also been carried out with the Swift observatory.The in-orbit performance of the SXT based on these observations and its comparison with the limited ground based tests will be presented,

9905-47, Session 10

In-orbit performance of UVIT on AstroSat

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The Ultraviolet Imaging telescope on ASTROSAT is a twin telescope (each of aperture 375 mm) capable of imaging in three channels. The FUV(130-180 nm) detector along with a filter wheel is mounted on one of the telescopes. The NUV (200-300 nm) and VIS (320-550 nm) detectors, along with one filter wheel each, are mounted on the second telescope, where a beam splitter is used to direct the NUV to the side port. The NUV and FUV detectors are used in the Photon counting mode and the VIS in the integration mode.

The filter wheels for FUV and NUV channels also carry gratings for slitless spectroscopy with low resolution.

The in-orbit calibrations are expected to estimate the spatial resolution, flat field corrections, photometric zero-points of the filter systems and the calibration of the grating.

9905-48, Session 10

In-orbit performance AstroSat CZTI

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The Cadmium-Zinc-Telluride Imager (CZTI) is one of the five payloads onboard recently launched Indian astronomy satellite Astrosat. CZTI is primarily designed for simultaneous hard X-ray imaging and spectroscopy of celestial X-ray sources. It employs the technique of coded mask imaging for measuring spectra in the energy lange of 20 – 150 keV. The detector plane of CZTI consists of total 64 CZT detector modules arranged in four identical quadrants. Each detector module has an active area of 16 cm2 and further divided into an array of 16 ? 16 pixels, each having size of 2.5 ? 2.5 mm2, resulting in total 16384 pixels over entire detector plane. As an added advantage, the fine pixilated nature of the detector plane of CZTI is also helpful in extending useful energy range to ~250 keV as well as possibly to measure polarization in hard X-rays, by identifying the X-ray photons interacting by means of Compton scattering. CZTI was the first scientific payload of Astrosat to be switched on after one week of the launch and was made operational during subsequent week. First phase of the CZTI performance verification observations consisted of deep imaging observations of the standard candle source, the Crab nebula as well as a black hole binary Cygnus X-1. Here we present preliminary results form the performance verification phase observations and discuss the in-orbit performance of CZTI.

9905-49, Session 11

The Neutron star Interior Composition Explorer (NICER): design and development

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During 2014 and 2015, NASA's Neutron star Interior Composition Explorer (NICER) mission proceeded successfully through Phase C, Design and Development. An X-ray (0.2–12 keV) astrophysics payload destined for the International Space Station, NICER is manifested for launch in the second half of 2016 on the Commercial Resupply Services SpaceX-11 flight. Its scientific objectives are to investigate the internal structure, dynamics, and energetics of neutron stars, the densest objects in the universe. During Phase C, flight components including optics, detectors, optical bench, pointing actuators, electronics, and others were subjected to environmental testing and integrated to form the flight payload. A custom-built facility was used to co-align and integrate the X-ray "concentrator" optics and silicon-drift detectors. Ground calibration provided robust performance measures of the optical (at NASA's Goddard Space Flight Center) and detector (at the Massachusetts Institute of Technology) subsystems, while comprehensive functional tests prior to payload-level environmental testing met all instrument performance requirements. We describe here the implementation of NICER's major subsystems, summarize their performance and calibration, and outline the component-level testing that was successfully applied.

9905-50, Session 11

NICER instrument detector subsystem: description and performance

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NICER (Neutron star Interior Composition Explorer) is an instrument that is planned to be deployed on the International Space Station. Its goal is to detect soft X-ray emission (0.2 - 12 keV) of neutron stars with unprecedented timing resolution of about 100 ns. The focal plane of the instrument is comprised of 56 Silicon Drift Detectors (SDD) manufactured by Amptek. Detectors form 7 groups of 8 SDDs, each group is controlled by an independent electronics box called MPU - Measurement and Power Unit. Signal from each SDD is fed to fast shaper with 84ns peaking time, and, in parallel, to slow shaper with 465ns peaking time. Fast shaper allows for accurate time stamping of the arriving photons, while slow shaper enables good energy resolution for spectroscopy. Ratio of fast to slow amplitudes also provides additional information about distance of the photon interaction from the detector center, thus helping to reject undesirable events at the periphery.

We will describe the main features of the system and will present the results of the measurements of the key parameters, such as quantum efficiency, energy resolution, timing properties, and other details of the instrument performance in the preflight testing.

9905-51, Session 12

Status of ART-XC/SRG instrument

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Spectrum Roentgen Gamma (SRG) is an X-ray astrophysical observatory, developed by Russia in collaboration with Germany. The mission will be launched in 2017 from Baikonur and placed in a 6-month-period halo orbit around L2. The scientific payload consists of two independent telescope arrays – a soft-x-ray survey instrument, eROSITA, being provided by Germany and a medium-x-ray-energy survey instrument ART-XC being

developed by Russia. ART-XC will consist of seven independent, but co-aligned, telescope modules. The ART-XC flight mirror modules have been developed and fabricated at the NASA Marshall Space Flight Center (MSFC). Each mirror module will be aligned with a focal plane CdTe double-sided strip detector which will operate over the energy range of 6-30 keV, with an angular resolution of <1?, a field of view of ~34? and an expected energy resolution of about 12% at 14 keV. The current status of the ART-XC/SRG instrument will be present.

9905-52, Session 12

eROSITA on SRG

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eROSITA (extended ROentgen Survey with an Imaging Telescope Array) is the core instrument on the Russian/German Spectrum-Roentgen-Gamma (SRG) mission which will be launched next year. eROSITA is now near its completion; The entire system is qualified, all flight components are finished and tested. All eight flight mirrors and flight cameras (including flight spares) underwent the final calibration. All subsystems and components are well within their expected performances. The end-to-end test with the complete telescope in our PANTER facility will be last step before shipment to Russia.

9905-53, Session 13

Localization algoritms for micro-channel x-ray telescope on board SVOM space mission

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SVOM is a French-Chinese space mission to be launched in 2021, and whose goal is the study of Gamma-Ray Bursts, the most powerful stellar explosions in the Universe. The Micro-channel X-ray Telescope (MXT) is an X-ray focusing telescope, on board SVOM, with a field of view of 1° (working in the 0.2-10 keV energy band), dedicated to the rapid follow-up of the Gamma-Ray Bursts counterparts and to its precise localization (smaller than 2 arc minutes). In order to reduce the optics mass and to have an angular resolution of few arc minutes, a configuration in "Lobster-Eye" has been chosen.

Using a numerical model of the MXT point spread function (PSF) we simulated MXT observations of point sources in order to develop and test different localization algorithms to be implemented on board MXT. We included preliminary estimations of the instrumental and sky background, as well as the effect of satellite stabilization after slew and potential detector defects such as dead columns and bright pixels.

The algorithms on board have to be a combination of speed and precision (the brightest sources are expected to be localized at a precision better than 10 arc seconds in the MXT reference frame). We present the comparison between different methods such as barycenter, PSF fitting in one or two dimensions.

The temporal performance of the algorithms is being tested using the X-ray afterglow data base of the XRT telescope on board the NASA Swift satellite.

9905-54, Session 13

THESEUS: the transient high-energy sky and early universe surveyor

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The Transient High Energy Sky and Early Universe Surveyor (THESEUS) is a mission concept developed by a large international collaboration aimed at exploiting Gamma-Ray Bursts for investigating the early Universe. The main scientific objectives of THESEUS include: investigating the star formation rate and metallicity evolution of the ISM and IGM up to redshift 10, detecting the first generation (pop III) of stars, studying the sources and physics of re-ionization, detecting the faint end of galaxies luminosity function. These goals will be achieved through a unique combination of instruments allowing GRB detection and arcmin localization over a broad FOV (more than 1sr) and an energy band extending from several MeVs down to 0.3 keV with unprecedented sensitivity, as well as on-board prompt (few minutes) follow-up with a 0.6m class IR telescope with both imaging and spectroscopic capabilities. Such instrumentation will also allow THESEUS to unveil and study the population of soft and sub-energetic GRBs, and, more in geeneral, perform monitoring and survey of the X_ray sky with unprecedented sensitivity.

9905-55, Session 13

DIOS: the Dark Baryon Exploring mission

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DIOS (Diffuse Intergalactic Oxygen Surveyor) is planned for a JAXA's small mission to be launched by Epsilon rocket around 2022. The purpose is to search for dark baryons through detecting red-shifted oxygen emission lines from warm-hot intergalactic medium (WHIM). The payload will consist of a TES microcalorimeter array, with energy resolution of a few eV, cooled with cryogen free refrigerators, and a 4-reflection X-ray telescope. The instrument will cover an energy range of 0.3 - 2 keV with a field of view of 30 - 50 arcmin diameter and an angular resolution of about 3 arcmin. The large field of view and very low background will give a high sensitivity for largely extended X-ray mission from earth's neighborhood, supernova remnants, galaxies and clusters of galaxies. The design of the spacecraft is in progress including the satellite bus system and thermal design of the payload. We also study to use a larger telescope up to about 1000 cm^2 at 1 keV, combined with a fast repointing function, to allow measurements of absorption lines from gamma-ray bursts. We report on the status of the design and expected science from DIOS.

9905-56, Session 13

A broadband x-ray imaging spectroscopy with high-angular resolution: the FORCE mission

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We are proposing FORCE (FOcusing Relativistic universe and Cosmic Evolution) as a next Japanese X-ray mission in the early 2020s. FORCE will be a medium-class mission after upcoming large-class X-ray mission ASTRO-H. ASTRO-H possesses a suite of sensitive instruments realizing the highest energy-resolution spectroscopy, a broadband X-ray imaging spectroscopy, and more. FORCE will take over a concept of the broadband X-ray imaging spectroscopy from ASTRO-H and reinforce it by significantly higher angular resolution. The current design of FORCE defines energy band pass of 1-80 keV with angular resolution of <15", achieving a 10 times higher sensitivity compared to previous missions above 10 keV with simultaneous soft X-ray coverage.

Our primary scientific objectives are to trace the cosmic evolution of black holes in various mass-scales, and to hunt for the nature of relativistic particles at various astrophysical shocks. How many heavily obscured (Compton-thick) Active Galactic Nuclei (AGNs) exist in the universe and what are their contributions to the total growth of supermassive black holes (SMBHs) are key questions to establish a complete picture of AGN evolution. Hard X-ray surveys above 10 keV are essential to census the Compton-thick AGN population and have started find a part of this population in the local universe. Our sensitive hard X-ray survey will prove more distant population and trace the cosmological growth. While it is believed that SMBHs gained most of their masses by accretion, the question how their ``seed'' black holes formed remains a big mystery. Ultra luminous X-ray sources in external galaxies are good candidates of such seed black holes. We will tackle their nature by tracing the state transition into dimmer X-ray regime that have not been explored ever. Searching for orphan stellar-mass blackholes in our Galaxy is also our scope. Non-thermal X-ray emission from relativistic particles at various astrophysical shocks provide us with essential information their nature and origin. Measuring time variability and small-scale structure above the synchrotron cut-off energy is a key to understand the particle acceleration mechanism in young supernova remnants. Detection of non-thermal X-ray emission from clusters of galaxies has long been awaited but not so far been successful. FORCE are going to open a new era in these fields.

FORCE will be launched with the Epsilon vehicle that is a Japanese solid-fuel rocket. FORCE carries three identical pairs of Super-mirror and wide-band X-ray detector. The focal length is currently assumed to be 10 m. The silicon mirror with multi-layer coating is our primary choice to achieve lightweight, good angular optics. The detector is a descendant of hard X-ray imager onboard ASTRO-H replacing its silicon strip with SOI-CMOS silicon pixel detector, allowing the low energy threshold down to 1 keV.

9905-57, Session 13

The X-Ray Surveyor mission concept study

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The X-Ray Surveyor is a successor to Chandra, with orders of magnitude improvements in sensitivity, field of view for sub-arcsec imaging, and effective area for grating spectroscopy and with high spectral resolution capabilities for extended objects. An X-ray observatory with such capabilities, operating in concert with other major astronomical facilities of the 2020-2030s, is required to address and solve some of the greatest challenges in modern astrophysics. The X-Ray Surveyor mission concept was recently selected by the NASA Astrophysics Director one of four missions to study for prioritization in the 2020 Astrophysics Decadal Survey. A formal concept study will be led by a NASA Center, selected by the Astrophysics Director, and executed under the guidance of a nominated Science and Technology Definition Team. The Study will be carried out over the next 3 to 4 years and products will include the science case for the mission, observatory performance requirements, a design reference mission, technology assessment, cost and top-level schedule for all of the major phases of the development. We will report on previous work to define a strawman concept for the X-Ray Surveyor and will summarize the plan forward.

9905-58, Session 13

eXTP: Enhanced X-ray Timing and Polarization mission

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eXTP - enhanced X-ray Timing and Polarization mission

eXTP is a science mission designed to study the state of matter under extreme conditions of density, gravity and magnetism. Primary goals are the determination of the equation of state of matter at supra-nuclear density (QCD theory), the measurement of QED effects in highly magnetized environments,and the test of predictions of General Relativity in strong-field regime of gravity. Primary targets include isolated and binary neutron stars, strong magnetic field systems like magnetars, and stellar-mass and supermassive black holes. The mission carries a unique and unprecedented suite of state-of-the-art scientific instruments enabling for the first time ever the simultaneous spectral-timing-polarimetry study of cosmic sources in the energy range 0.5-30 keV. Key elements of the payload are: the low-energy Focusing Array (LFA) - a set of 11 X-ray optics (PSF 1') for a total effective area of 1 and 0.6 m2 at 2 keV and 6 keV, respectively, equipped with Silicon detectors offering <180 eV spectral resolution; the large Area Detector (LAD) - a deployable set of 640 Silicon drift detectors, for a total effective area of 3.4 m2 and spectral resolution of beteer than 250-300 eV, with field of view collimated to 1 degree by capillary plate technologies; the Gas Pixelated Detector (GPD) – a set of 2 X-ray optics (PSF 15"), for a total effective area of 1700 cm2 and 1100 cm2 at 2 keV and 6 keV, respectively, equipped with imaging gas-pixelated detector photo-electric polarimeters; and the Wide Field Monitor (WFM) – a set of 6 coded-mask, wide field camera units, equipped with position-sensitive Silicon drift detectors, each covering a 90 degrees x 90 degrees field of view.

The eXTP international consortium is primarily made of major institutions of the Chinese Academy of Sciences and universities in China, as well as several major institutions in several European countries. The predecessor of eXTP is the XTP mission, selected and funded as one of the so-called background missions in the Strategic Pioneering Space Science Program of the Chinese Academy of Sciences since 2011. The strong European participation has enhanced the scientific capabilities of eXTP significantly. Given the core objectives of the mission, eXTP is fully complementary to ESA's ATHENA mission. The planned launch time of eXTP is between 2023 and 2025.

The presentation is made on behalf of the whole eXTP consortium.

9905-59, Session 13

The LOFT mission concept: a status update

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The Large Observatory For x-ray Timing (LOFT) is a mission concept which was proposed to ESA as M3 and M4 candidate in the framework of the Cosmic Vision 2015-2025 program. Thanks to the unprecedented combination of effective area and spectral resolution of its main instrument, and the uniquely large field of view of its wide field monitor, LOFT will study the behaviour of matter in extreme conditions such as the strong gravitational field in the innermost regions close to black holes and neutron stars, and the supranuclear densities in the interiors of neutron stars. The science payload is based on a Large Area Detector (LAD, >8m2 effective area, 2-30 keV, 240 eV spctral resolution, 1 degree collimated field of view) and a Wide Field Monitor (WFM, 2-50 keV, 4 steradian field of view, 1 arcmin source location accuracy, 300 eV spectral resolution). The WFM is equipped with an on-board system for bright events (e.g. GRB) localization. The trigger time and position of these events are broadcast to the ground within 30 s from discovery. In this paper we will present the current technical and programmatic status of the mission.

9905-60, Session 14

High-resolution lightweight x-ray optics

William W. Zhang, NASA Goddard Space Flight Ctr. (United States)

Optics plays a uniquely important role in determining the capability of an observatory. Future observatories must be qualitatively better than current ones in angular resolution and/or effective area. In this paper we report on an effort whose objective is to eventually achieve diffraction-limited x-ray optics that is both lightweight and affordable, enabling future x-ray observatories that are a match to optical observatories such as HST and JWST in image quality. Our program has five technical elements: substrate fabrication, coating, alignment, bonding, and systems engineering. We have made significant and steady progress in each of these five areas in the last few years, culminating in progressively better angular resolution and technical readiness while keeping the mirror lightweight. We are well on our way to realize x-ray astronomers' dream of a high-resolution (~1" or better) and large effective area (>1 m2) telescope, such as the x-ray surveyor being studied by NASA.

9905-61, Session 14

Beyond Chandra: problems, solutions, and perspectives for the implementation of very high angular resolution x-ray telescopes in the new millennium

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An important challenge for the X-ray astronomy of the new millennium is represented by the implementation of an X-ray telescope able to maintain the exquisite angular resolution of Chandra (sub-arcsec on axis) but, at the same time, being characterized by a much larger throughput and grasp. A mission with similar characteristics is represented by the X-ray Surveyor Mission, recently proposed in USA at a level of concept. The mission is an effective area of more than 2 square meters at 1 keV (i.e. 30 greater than Chandra) and a 15-arcminute diameter field-of-view with one-arcsecond or better half-power diameter (versus the 4 arcmin diameter of Chandra). While the scientific reasons for implementing a similar mission are clear, being related to compelling problems like e.g. the formation and subsequent growth of black hole seeds at very high redshift or the identification of the first galaxy groups and proto-clusters, the realization of an optics system able to fulfil these specs remain challenging. Different technologies are being envisaged, like the use of adjustable segmented mirrors (with use of piezoelectric or magneto-restrictive film actuators on the back surface) or the direct polishing of a variety of thin substrates or the use of innovative correction methods like the differential deposition, the ion-figuring removal of error profile or the correction via controlled stress films. In this paper the problematic will be deeply discussed, comparing pros and cons of the different technological approaches and configurations (including the question of monolithic versus segmented optics options). Finally, an update will be given on the progresses achieved on direct polishing of thin SiO_2 substrates (monolithic and segmented).

9905-62, Session 14

Development of 0.5 arcsecond adjustable x-ray optics: status update

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Adjustable grazing incidence X-ray optics represent a candidate technology for the development of the successor to the Chandra X-ray Observatory. The adjustable optics, produced by depositing a thin film of piezoelectric material on the back surface of a Wolter mirror segment, represents a way in which mirror figure errors resulting from fabrication and mounting can be corrected once on the ground. After launch, it may also be feasible to make on-orbit corrections for figure changes due to thermal effects. This powerful technology does not require massive reaction structures, and will make possible the simultaneous achievement of very large effective area and sub-arcsecond X-ray imaging.

We describe recent progress in our continuing development of adjustable X-ray optics. We discuss development of a mirror segment alignment approach consistent with sub-arcsecond imaging, demonstration of deterministic figure correction on cylindrical test mirrors, the use of strain gauges for in situ monitoring of piezoelectric performance, and progress towards X-ray testing of a mounted, aligned, and corrected pair of mirrors.

9905-63, Session 14

Development of the a direct fabrication technique for full-shell x-ray optics

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The Chandra observatory demonstrated that modern fabrication techniques can provide sub-arcsecond-resolution grazing-incidence optics if thick mirror substrates are used. The challenge to meet the optics requirements for future astrophysical missions is to develop the optical fabrication technology capable of producing Chandra-like optics but with an order of magnitude lighter mirror shells and at an affordable price. Towards realizing this goal at MSFC we are using full-shell thin-metal substrates to provide the necessary stiffness and a modern robotic polishing machine which can converge to a low level of surface error quickly.

Ideally, the mirror shell has low density, low coefficient of expansion (CTE), high modulus of elasticity and high yield strength. It should also be a material that is not too difficult to figure and polish. Beryllium has excellent mechanical properties for an optic substrate. Also beryllium can be coated with Nickel/Phosphorous (NiP) alloy, a hard material which can be easily figured and polished/superpolished. The CTE of beryllium alloy can be matched to the NiP by adding aluminum to the alloy and is very close to stainless steel, so for future telescopes such mirrors would be easy to mount in a thermally stable system. However, while highly desirable as a substrate the cost of beryllium is quite high and so we are using aluminum substrates coated with NiP as mechanical surrogates during our early development.

One of the challenges for thin-shell fabrication is to support the shell during processing so that, at one extreme, it cannot fracture or microyield, but also cannot deflect enough to affect the polishing itself. The optics backing systems developed for diamond turning of inner and outer surfaces of the substrate and for the polishing will be presented along with the ex-situ and in-situ metrology techniques used.

To perform the mirror surface error correction deterministically using the computer controlled polishing machine the measured surface figure profiles need to be converted into the polishing tool path profile. The wear patterns are characterized for a specific slurry and polishing pad material and these data area used to generate the appropriate polishing-tool velocity profile to apply the necessary figure correction. The polishing tool model is developed to streamline the optimization of the polishing tool generation process. Results of polishing experiments to validate the model using NiP plated samples will be presented. The validated model has been used for the generation of polishing tool paths to reduce the surface errors of the x-ray optics to sub-arcsecond levels. Results of these polishing experiments will be also presented.

9905-64, Session 14

Advancements in x-ray reflection gratings for space-based applications

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Many of the key science goals in X-ray astronomy require spectroscopy in the soft energy band, 0.2 - 2.0 keV. The performance requirements placed on spectrometers typically have spectral resolving powers in the thousands with effective areas in the hundreds of square centimeters. Obtaining both of these requirements in a single instrument is a challenge for a variety of reasons. Here, we discuss the development tasks specific to off-plane reflection gratings. We detail the requirements that drive our technical challenges such as fabrication, alignment, and integration. Finally, we summarize the plans for utilizing off-plane grating arrays on suborbital rockets and Explorers, in addition to discussing their applicability to Probe and Observatory class missions.

9905-65, Session 14

Critical-angle x-ray transmission grating spectrometer with high resolving power and extended bandpass

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A number of high priority questions in astrophysics can be addressed by a state-of-the-art soft x-ray grating spectrometer, such as the role of Active Galactic Nuclei in galaxy and star formation, characterization of the Warm-Hot Intergalactic Medium and the "missing baryon" problem, characterization of halos around the Milky Way and nearby galaxies, as well as stellar coronae and surrounding winds and disks. An Explorer-scale, large-area (> 1,000 cm2), high resolving power (R ??lambda/delta_lambda > 3,000) soft x-ray grating spectrometer is highly feasible based on Critical-Angle Transmission (CAT) grating technology. Still significantly higher performance can be provided by a CAT grating spectrometer on an X-ray-Surveyor-type mission. CAT gratings combine the advantages of blazed reflection gratings (high efficiency, use of higher diffraction orders) with those of conventional transmission gratings (low mass, relaxed alignment tolerances and temperature requirements, transparent at higher energies) with minimal mission resource requirements. They are high-efficiency blazed transmission gratings that consist of freestanding, ultra-high aspect-ratio grating bars fabricated from silicon-on-insulator (SOI) wafers using advanced anisotropic dry and wet etch techniques. Blazing is achieved through grazing-incidence reflection off the smooth grating bar sidewalls. The reflection properties of silicon are well matched to the soft x-ray band. Nevertheless, CAT gratings with sidewalls made of higher atomic number elements allow extension of the CAT grating principle to higher energies and larger dispersion angles. We show x-ray data from metal-coated CAT gratings and demonstrate efficient blazing to higher energies and larger blaze angles than possible with silicon alone. We also report on measurements of the resolving power of a breadboard CAT grating spectrometer consisting of a Wolter-I slumped-glass focusing mirror pair from Goddard Space Flight Center and CAT gratings, performed at the Marshall Space Flight Center Stray Light Facility.

9905-215, Session PS7

Thermal forming of glass substrates for X-ray Surveyor optics

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The X-ray surveyor mission concept aims to the construction of an observatory with Chandra-like angular resoution and 30 times more effective area or larger. The technology under development at SAO is based on the deposition of piezoelectric material on the back of thermally formed Wolter segments made of thin glass. About 8000 mirror segments, with initial quality of 10 arcseconds or better are required for the telecope. In this paper we review the progress and current status of thermal forming activities conducted in last years at SAO, highlighting the most relevant technical problems and the way to solve them.

9905-216, Session PS7

The SVOM/GRM mass model and background monte-carlo simulations

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The Space multi-band Variable Object Monitor (SVOM) mission is a wide band observatory designed for making observations of Gamma Ray Bursts (GRB) from the visible band to gamma ray band, which is expected to launch around year of 2021.

GRM (Gamma Ray Monitor) is a GRB trigger detector on aboard SVOM. GRM detects a large portion of the sky in the hard X-ray and soft gamma-ray band with a PS/NaI(Tl) phoswich detector. The energy range is 15-5000 keV. GRM has 3 GRD (Gamma Ray Detector) units.The elevation angle of each GRD relative to the symmetry axis is set to 30° and the interval in azimuth angle of 3 GRDs is 120°. Rough localization can be achieved in a large Field of View using only 3 GRDs, which may contribute to the gravitational wave measurement.

In order to evaluate the number of bursts detected and the GRB spectrum description, we have some research on the background of GRM. Also simulated background level is necessary for the signal noise ratio (SNR) calculation. We make use of the mass modeling technique to estimate the total background. It consists of three steps. First, we built a fine geometric model of GRM and a coarse model of the other payloads. Then based on the investigation about the space environment concerning SVOM low-earth orbit, in our simulation we considered cosmic rays, cosmic X-ray background (CXB), South Atlantic Anomaly (SAA) trapped particles, the albedo gamma, and neutrons from interaction of cosmic rays with the Earth's atmosphere. Finally, the Shielding Physics List supplied by Geant4

collaborations was adopted. According to our simulation, we find that CXB dominates the total background because of GRM's large field of view (for each GRD, the FOV is +/-60 degree with respect to its symmetry axis). When the Earth locates behind the SVOM, the total background of each GRD is approximately 1081 count/s on average over 15–5000 keV energy band after 100 days in orbit, and approximately 800 count/s comes from the CXB. As SVOM adopts the anti-sun pointing strategy, the Earth will in the FOV of GRM in some situation definitely. When the GRD observes facing the Earth, the total background reduces to approximately 659 count/s because of the Earth shielding, and CXB induced background reduces to 290 count/s. So we got a function about the total background level with respect to the Earth-SVOM pointing angle by fitting 12 discrete data in different pointing angels. We also find that in the energy band larger than 300 keV, delayed background come from the SAA trapped particles become prominent.

9905-217, Session PS7

The SVOM microchannel x-ray telescope status

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We present the PDR design status Microchannel X-ray Telescope (MXT), a new telescope that will be flying on the Sino-French space mission SVOM dedicated to Gamma-Ray Burst (GRB) science. SVOM will carry a multi wavelength payload, which includes 2 instruments provided by France (ECLAIRs and MXT) and two provided by China (GRMs and VT). ECLAIRs is a wide field of view (2 sr) coded mask telescope, triggering in the 4 - 250 keV, and providing the initial GRB alerts. ECLAIRs is complemented by the GRMs, a set of three wide field non-imaging gamma-ray (30 keV - 5 MeV) NaI spectrometers. Two narrow field instruments, a visible telescope, VT, and the MXT, will point the GRB location, after an autonomous slew of the satellite, in order to study in detail the GRB afterglows, and to pinpoint the GRB locations.

MXT is being developed under the responsibility of CNES Toulouse, in tight collaboration with CEA-Irfu, MPE Garching, and the University of Leicester. Its current design is based on the coupling of square 40 microns micro-pore optics (MPOs) with an actively cooled (-65°C) pnCCD (made of 256 x 256 pixels of 75 microns) developed at MPE/HLL in the context of the DUO mission.

MXT is a compact and light (<35 kg) focussing X-ray telescope with a 1 m focal length, which will provide an effective area of about 50 square cm on axis. Its point spread function (PSF) is expected to be better than 4.5 arc min (FWHM), and its sensitivity (~2e-12 erg/cmsq/s for a 10 ks observation) adequate to detect practically all the X-ray afterglows of the SVOM GRBs.

MXT is expected to localize 90 (50)% of SVOM GRB afterglows to better than 60 (20) arc sec (90% confidence radius, no systematic errors included) after five minutes of observation from the satellite stabilisation. We present MXT the status of the design of the different MXT sub-systems, as well as, the associated preliminary bread-board results.

9905-218, Session PS7

Arcus: the x-ray grating spectrometer explorer

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Arcus will be proposed to the NASA Explorer program as a free-flying satellite mission that will enable high-resolution soft X-ray spectroscopy with unprecedented sensitivity - effective areas of >500 sq cm and spectral resolution up to 3000. The Arcus key science goals are (1) to measure the effects of structure formation imprinted upon the hot baryons that are predicted to lie in extended halos around galaxies, groups, and clusters, (2) to trace the propagation of outflowing mass, energy and momentum from the vicinity of the black hole out to large scales as a measure of their feedback and (3) to understand how stars, circumstellar disks and exoplanet atmospheres form and evolve.

Arcus relies upon grazing-incidence silicon pore X-ray optics with the same 12m focal length (achieved using an extendable optical bench) that will be used for the ESA Athena mission. The focused X-rays from these optics will then be diffracted by high-efficiency off-plane reflection gratings that have already been demonstrated on sub-orbital rocket flights, imaging the results with flight-proven CCD detectors and electronics. The power and telemetry requirements on the spacecraft are modest. Mission operations are not complex, as most observations will be long (~100 ksec), uninterrupted, and pre-planned, although there will be limited ToO capabilities to observe sources such as tidal disruption events or supernovae. After the end of prime science, we plan to allow guest observations to maximize the science return of Arcus to the community.

9905-219, Session PS7

Multi-directional measurements of high energy particles from the Sun-Earth L1 point with STEPS

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Supra Thermal Energetic Particle Spectrometer (STEPS) is an independent sub system of the ASPEX experiment. ASPEX (Aditya Solar Wind Particle EXperiment) has been selected as one of the possible experiments onboard the Aditya - L1 mission (forthcoming Indian solar mission), which is to be placed in a halo orbit around the L1 Lagrangian point, lying between the Sun and the Earth at a distance of 1.5 million km from the Earth. Primary objective of the ASPEX experiment is to make in - situ, multi - directional measurements of solar wind supra-thermal and high

energy particles in the energy range of 100 eV/n to 5 MeV/n. The ASPEX payload has two independent subsystems – STEPS, which will measure the energy spectrum of high energetic particles from six multiple directions, in the energy range of 20 keV/n to 5 MeV/n; and SWIS (Solar Wind Ion Spectrometer), which will measure the angular and energy distributions of Solar wind ions in the energy range of 100 eV to 20 keV, using the technique of electro-static analysis (ESA) followed by magnetic separation of particles.

The STEPS instrument has been configured into three packages: viz. the STEPS - 1 detector package, the STEPS - 2 detector package and the processing electronics package. The STEPS - 1 detector package has 4 detector units, pointing in 4 different directions with each having a different field of view. In this package, 2 detector units will provide particle species differentiated (proton and alpha) energy spectra while other 2 detector units will provide particle species integrated energy spectra. Similarly STEPS - 2 detector package has 2 detector units, one detector will provide species differentiated energy spectra, while other unit will provide species integrated energy spectra.

The detector units of STEPS measuring species differentiated energy spectra, will use a specially designed Si detectors along with plastic Scintillators for particle detection. Si detectors are fabricated in a single package with two different thicknesses of dead layers (0.1 ?m and 1.0 ?m) of high Z material. The Plastic Scintillator is placed below the Si detector package, which provides a possibility of measuring particles up to very high energy (~50 MeV/n) along with particle identification using ?E-E mode. The detector units of STEPS measuring species integrated spectra will use a standard Si-PIN detector.

In this paper, we will describe the overall configuration of the STEPS subsystem and present the salient feature of STEPS. We will present the development status of the bread - board model with some preliminary results.

9905-220, Session PS7

Optical design considerations and raytracing results for the Arcus grating spectrometer concept

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Arcus is a mission concept for a next generation X-ray grating spectrometer. It will offer spectral resolution greater than 2000 combined with over 500 cm^2 of effective area at the 2.1-2.4 nm bandpass. These capabilities will elucidate the cycle of baryonic matter in and out of galaxies, the means by which supermassive black holes influence their surroundings, and the early formation and evolution of solar systems. We present the overall optical design of the mission, which features four arrays of silicon pore optics modules with four matching arrays of off-plane reflection grating modules. These optics disperse the incident X-rays over the 12 m focal length in four separate conical diffraction patterns onto CCD arrays at the focal plane. Each array of optics is an azimuthal sub-aperture of the typical Wolter telescope design, enabling enhanced spectral resolution due to an asymmetric point spread function. Coatings for the silicon pore optics and gratings featuring B4C have been baselined to optimize throughput in the 0.8-5 nm mission bandpass. The theoretical spectral resolution, effective area, and alignment tolerances have been determined via a high fidelity raytrace model. This model has been optimized using an observation time metric derived from the mission science program.

9905-221, Session PS7

Exploring the formation and evolution of clusters, galaxies, and stars with Arcus

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I will discuss the scientific research objectives of Arcus, a NASA/MIDEX mission under development in response to the 2017 call for proposals. It is a free-flying, soft X-ray grating spectrometer with the highest-ever spectral resolution in the energy range. The Arcus bandpass includes the most sensitive tracers of diffuse million-degree gas, spectral lines from O VII and O VIII, along with many other diagnostics, such as H- and He-like lines of C, N, Ne and Mg, and unique density- and temperature-sensitive lines from Si and Fe ions. These capabilities enable an advance in our understanding of the formation and evolution of baryons in the Universe that is unachievable with any other present or planned observatory. The mission will address multiple key questions posed in the Decadal Survey and NASA's 2013 Roadmap: How do baryons cycle in and out of galaxies? How do black holes and stars grow and influence their surroundings and the cosmic web via feedback? How do stars, circumstellar disks and exoplanet atmospheres form and evolve? Arcus data will answer these questions by measuring X-ray emission and absorption spectra at high resolution from a wide range of sources within and beyond the Milky Way. This will be accomplished by leveraging recent technical developments in off-plane gratings and silicon pore optics. CCDs with strong Suzaku heritage combined with electronics based on the Swift mission will detect the dispersed X-rays. Arcus will support a broad astrophysical research program, and its superior resolution and sensitivity in soft X-rays will complement the forthcoming Astro-H and Athena calorimeters that have high resolution above 2 keV.

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End-to-end simulations for Arcus

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We present an overview of the end to end simulation software developed for the proposed Arcus mission. Consisting of off-plane gratings behind silicon pore optics, Arcus will provide a resolution of >2000 in the soft 0.25-1.5keV X-ray regime with a high effective area of >500cm^2, recovering a substantial fraction of the X-ray gratings science originally envisioned for the International X-ray Observatory.

As part of the Arcus concept study we have developed a full simulation chain for Arcus that is able to model in a realistic way all properties of the Arcus instrument that are relevant for its measurement process. We use the SIXTE Monte-Carlo modeling and simulation framework (http://www.sternwarte.uni-erlangen.de/sixte) to model as-detected X-ray source photon distributions. We employ such simulations both for simulation of observations, but also to generate instrument responses (effective areas and line spread functions) which may not be explicitly known a priori. Models of the expected particle background will also be included. We illustrate the simulation chain using several typical applications and demonstrate the feasibility of the envisaged Arcus design. These simulations will also establish both diffuse X-ray and particle background requirements and thus potentially impact the choice of orbit. These tools can be easily generalized for use with other X-ray gratings mission concepts such as an X-ray gratings probe or the “X-ray Surveyor” concept.

9905-223, Session PS7

The protoMIRAX hard x-ray balloon experiment: a pathfinder for MIRAX

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We present the development status of the protoMIRAX hard X-ray balloon experiment, which is a prototype designed to test in near-space environment several subsystems of the MIRAX satellite mission. The main instrument is a wide-field (20 x 20 degrees) hard X-ray (10-200 keV) imaging camera that utilizes an array of 169 (13x13) planar CdZnTe detectors with dimensions 10mm x 10mm x 2mm, a collimator and a coded mask. The angular resolution in the balloon configuration is 1.5 degrees. The coded mask employs an extended 13x13 MURA pattern and is built with Pb-Sn-Cu layers supported by an acrylic frame. We show laboratory calibration results and detailed Monte Carlo GEANT4 simulations of the performance of the instrument at balloon altitudes and also at the expected near-equatorial circular low-Earth orbit of MIRAX. The simulations results allowed us to redesign the shielding and collimator materials and geometry in order to minimize the background and make the spatial distribution of background counts uniform across the detector plane. We also present the electronics solutions we have developed for the data acquisition system and the data handling on-board computer. protoMIRAX will be launched for the first time in late 2016.

9905-224, Session PS7

Update on the micro-X sounding rocket x-ray telescope

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Micro-X is a sounding rocket borne X-ray telescope that utilizes Transition Edge Sensors in order to do imaging spectroscopy with a high level of energy resolution. The detectors are held at 75 mK via an Adiabatic Demagnetization Refrigerator which uses a Ferric Ammonium Alum salt pill. The detector array has 128 pixels and an effective area of 300 cm2, with a field of view of 11.8 arcmin in its present layout. We present an update of ongoing progress in preparation for the upcoming launch of the instrument.

9905-225, Session PS7

Alignment and metrology of a high fidelity grating module prototype for the Arcus mission concept

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Arcus is a mission concept for a next generation X-ray grating spectrometer. It will offer spectral resolution greater than 2000 combined with over 500 cm^2 of effective area at the 2.1-2.4 nm bandpass. To demonstrate the technical feasibility of such a mission, we have designed and fabricated a prototype grating module. The alignment tolerances of the grating module are reviewed and the metrology techniques used to achieve these tolerances are covered in detail. We describe the gratings used to populate this module and the results of the alignment and figure metrology during alignment. The module will be tested along with a prototype 12 m focal length silicon pore optics module at the PANTER beamline this summer.

9905-226, Session PS7

The CubeSat imaging x-ray solar spectrometer (CubIXSS) mission concept

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The CubeSat Imaging X-ray Solar Spectrometer (CubIXSS) is a nanosatellite mission concept to measure spectrally- and spatially-resolved soft X-ray (SXR) emission from the quiescent and flaring Sun using a 6U CubeSat platform in low-Earth orbit during a nominal 1-year mission. The CubIXSS instrument suite comprises two spectrometers and a slitless imaging spectrograph: the Small Assembly for Solar Spectroscopy (SASS) and the Multi-Order X-ray Spectral Imager (MOXSI), respectively. The copious solar SXR flux allows for precise measurements even with pinhole apertures, ideal for the limited resources of a CubeSat envelope.

The ~1 MK solar corona is ~100x hotter than the underlying chromosphere, and can reach ~50 MK or higher during solar flares. Exactly how the corona attains such high temperatures remains one of the fundamental unanswered questions in solar physics. There has been a general lack of spectrally-resolved observations of solar SXRs from ~0.2 to 5 keV (~0.25-6 nm), an energy range dominated by emission from hot coronal plasma. These SXRs also drive dynamical processes in Earth's ionosphere that affect communications, atmospheric composition, and satellite drag. Accurate SXR measurements in this range would thus provide crucial diagnostics of plasma heating during both solar flares and quiescent times, and aid in modeling and understanding Earth's atmospheric response to these X-rays.

SASS utilizes the Amptek X123-SDD silicon drift detector, a low-noise, commercial off-the-shelf (COTS) instrument enabling spatially-integrated solar SXR spectroscopy from ~0.5 to ~30 keV with ~0.15 keV FWHM spectral resolution and ~few-sec cadence with low power, mass, and volume requirements. Two detectors with tailored filters and pinhole aperture sizes provide sensitivity over all activity levels, from solar minimum to >X5 flares, from only ~0.03 mm^2 total illuminated area. Two X123-CdTe cadmium-telluride detectors, with ~50 mm^2 total illuminated area, provide ~5-100 keV hard X-ray (HXR) spectroscopy with ~0.5-1 keV FWHM resolution to extend the high-energy response during flares. The precise spectra from SASS will provide detailed measurements of the coronal temperature distribution during flares and quiescent times, along with context information of HXR-emitting flare-accelerated electrons.

MOXSI is a novel spectro-spatial imager -- the first ever solar imager on a CubeSat -- utilizing a custom pinhole camera and Chandra-heritage X-ray transmission diffraction grating to provide spatially-resolved, full-Sun imaging spectroscopy from ~1 to ~55 Å (~0.2-10 keV) with ~25 arcsec and ~0.25 Å FWHM spatial and spectral resolutions, respectively, and cadence of ~few tens of sec. MOXSI's unique capabilities enable SXR spectroscopy and temperature diagnostics of individual flares and active regions.

Through these new measurements, CubIXSS will improve our physical understanding of thermal plasma processes and impulsive energy release in the solar corona, from quiet Sun to solar flares, and the impact of solar X-rays on Earth's upper atmosphere.

9905-227, Session PS7

Fast simulation of the NICER instrument

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The NICER mission uses a complicated physical system to collect information from objects that are, by x-ray timing science standards, rather faint. To get the most out of the data we will need a rigorous understanding of all instumental effects. We are in the process of constructing a very fast, high fidelity simulator that will help us to assess instrument performance, support simulation-based data reduction, and improve our estimates of measurement error. We will combine and extend existing optics, detector, and electronics simulations. We will employ the Compute Unified Device Architecture (CUDA) to parallelize these calculations. The price of suitable CUDA-compatible multi-gigaflop cores is about $0.20/core, so this approach will be very cost-effective.

9905-228, Session PS7

Ground calibration of the SDDs for NICER

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The Neutron star Interior Composition ExploreR (NICER) is set to be deployed on the International Space Station (ISS) in early 2017. It will use an array of 56 Silicon Drift Detectors (SDDs) to detect soft X-rays (0.2 - 12 keV) with 100 nanosecond timing resolution. Here we describe the effort to calibrate the detectors in the lab primarily using a Modulated X-ray Source (MXS).

9905-229, Session PS7

Performance of NICER flight x-ray concentrator

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Neutron star Interior Composition ExploreR (NICER) is a NASA instrument proposed to the Mission of Opportunity (MoO) and will be delivered to the International Space Station (ISS) by SpaceX-11 Falcon 9 launch vehicle in August, 2016. NICER is dedicated to the study of the extraordinary gravitational, electromagnetic, and nuclear-physics environments embodied by neutron stars. It features a high timing resolution of less than a few hundred nsec with a large collecting area twice as much as XMM-Newton at the 1-2 keV band. The NICER timing instrument consists of 56 X-ray optic and detector pairs, an X-ray Concentrator (XRC) and a silicon drift detector. Each XRC is based on an epoxy replicated thin aluminum foil X-ray mirror, similar to those of Suzaku and ASTRO-H, but only single stage parabolic grazing incidence optic. Each has a focal length of 1.085 m and a diameter of 100 mm, with 24 confocally aligned parabolic shells.

Grazing incident angles to individual shells range from 0.4 to 1.4 deg. The flight 56 XRCs have been completed and successfully delivered to the payload integration. All the XRC was characterized at the GSFC 100-m X-ray beamline using 1.5 and 4.5 keV X-rays. The XRC performance, effective area and point spread function, was measured by a CCD camera and a proportional counter. The average effective area is about 44 cm^2 at 1.5 keV and about 18 cm^2 at 4.5 keV, which is consistent with a micro-roughness of 5 A from individual shell reflectivity measurements. The XRC focuses about 91% of X-rays into a 2 mm aperture at the focal plan, which is the NICER detector window size. Each XRC weighs only 325 g. These performance met the project requirement. In this paper, we will present summary of the flight XRC

performance as well as co-alignment results of the 56 XRCs on the flight payload as it is important to estimate the total effective for astronomical observations. We are also developing a ray-tracing simulator in order to reproduce the XRC performance and generate a response, which will be used in astrophysical discussion. We will present comparison between the measured performance and the ray-tracing simulations.

9905-230, Session PS7

Large observatory for x-ray timing (LOFT-P): a probe-class mission concept study

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LOFT-P is a mission concept for a NASA Astrophysics Probe-Class (<$1B) X-ray timing mission, based on the LOFT M-class concept originally proposed to ESA's M3 and M4 calls. LOFT-P requires very large collecting area, high time resolution, good spectral resolution,broadband spectral coverage (2-30 keV), highly flexible scheduling, and an ability to detect and respond promptly to time-critical targets of opportunity. It addresses science questions such as: What is the equation of state of ultra dense matter? What are the effects of strong gravity on matter spiraling into black holes? It would be optimized for sub-millisecond timing of bright Galactic X-ray sources including X-ray bursters, black hole binaries, and magnetars to study phenomena at the natural timescales of neutron star surfaces and black hole event horizons and to measure mass and spin of black holes. These measurements are synergistic to imaging and high-resolution spectroscopy instruments, addressing much smaller distance scales than are possible without very long baseline X-ray interferometry, and using complementary techniques to address the geometry and dynamics of emission regions. LOFT-P would have an effective area of >6 m2, >10x that of the highly successful Rossi X-ray Timing Explorer (RXTE). A sky monitor (~2-50 keV) acts as a trigger for pointed observations, providing high duty cycle, high time resolution monitoring of the X-ray sky with ~20 times the sensitivity of the RXTE All-Sky Monitor, enabling multi-wavelength and multi-messenger studies. A probe-class mission concept would employ lightweight collimator technology and large-area solid-state detectors, segmented into pixels or strips, technologies which have been recently greatly advanced during the ESA M-3 Phase A study of LOFT. Given the large community interested in LOFT (>800 supporters, (http://www.isdc.unige.ch/loft/index.php/loft-team/community-members), the scientific productivity of this mission is expected to be very high, similar to or greater than RXTE (~2000 refereed publications.) In 2016, MSFC's Advanced Concepts Office will perform a study of a US-led probe-class LOFT concept. We will report on the current status of this study of LOFT-P. NRL's work on X-ray astrophysics is funded by the Chief of Naval Research (CNR)

9905-231, Session PS7

Verification and in-orbit-prediction of the eROSITA thermal control system

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The X-ray telescope eROSITA is the core instrument on the Russian Spektrum-Roentgen-Gamma mission, accompanied by the Russian ART-XC telescope. Besides an all-sky survey, also pointed observations will be performed in the energy range between 0.1-10 keV. Main goal of the mission is the detection of 100.000 galaxy clusters in order to constrain cosmological parameters, such as the density and evolution of dark energy.

With launch scheduled for 2017, the project is in its final stage, with the calibration ongoing. All major environmental tests with the qualification model have been performed successfully. Especially the thermal control system was qualified in a space simulation test, and meanwhile also the flight components have been manufactured and tested extensively.

All test results, gained over the years, can now be combined to an overall picture of the thermal behavior of the instrument. Not only operational and non-operational temperature ranges have been identified, also uncertainty analysis has been done.

Finally, accurate in-orbit predictions are possible. With the given boundary conditions at the Lagrangian point 2 (L2), we expect a rather stable performance, only modified by different positions on the orbit around L2. Different load cases have been examined to have reliable data for the mission.

9905-232, Session PS7

ART-XC/SRG: results of qualification thermo-vacuum test

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ART-XC – a medium-x-ray-energy survey instrument of SRG project is being developed in Russia under the leadership of the Space Research Institute (IKI).

Main requirements to the telescope temperature control system are provided by two key elements – module of seven semiconductor DSSD CdTe detectors which have to operate at the temperature -22.5±2.5 C to prevent CdTe crystals fast polarization (large polarization time allows to keep detector energy spectral characteristics during continuous 2 – 3 days expositions) and the module of seven mirror systems which have to operate at a temperature 20±2 C (which is the temperature used in the on Earth mirror systems calibration tests).

Thermal control system ART-XC consists of 36 variable film heaters placed in different places on the telescope structure and controlled according to indications of thermal sensors. The maximum power of each heater is 10 W. There are 21 heaters located on seven mirror systems. Each mirror system case is equipped with two heaters, additional one is located on the mirror system baffle. Seven heaters are placed on detectors. Remaining eight heaters are placed in different telescope parts – one on the protective cover, one on the explosive pin, one under the star tracker, three on the mirror system and star tracker mount plate, one on the detector block mount plate and one on the calibration sources control system block. Thermal control system constantly checks temperature from 36 thermal sensors and regulate the heater's power supply. There is one passive thermal control element in the telescope – radiator, which is connected to detectors via three heat pipes and cools them down.

The QM (qualification model) of ART-XC was manufacture and tests of it were operated. QM completely corresponds to flight model. Conditions of thermo-vacuum tests were corresponded to real external thermal conditions in flight. The vacuum, cold of space, temperature of mounting planes and shielding by eRosita telescope were reproduced at this test. During test various thermal telescope modes include orbital injection were simulated.

Results of the QM thermo-vacuum test are presented in this paper.

9905-233, Session PS7

Results of ground tests and calibration of x-ray focal plane detectors for ART-XC/SRG instrument

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The Russian Space Research Institute (IKI) has developed seven flight models and three spare models of the X-ray detectors for the ART-XC/SRG telescope.

Each detector situated in the focal plane of ART-XC X-ray optics and includes CdTe die, front-end electronics, data processing, storage and telemetry units.

CdTe dies manufactured by Acrorad (Japan). Each die has a double side strip electrodes configuration (48 strips and guard ring on top side and 48 strips and guard ring on bottom side of the die). The die dimensions is 30?30?1 mm.

We used VA64TA1 ASICs manufactured by Ideas (Norway) as front-end electronics. We need two ASICs per one detector (one for bottom side and one for top side). Due to nature of the double side strip detectors, we obtain spectroscopy from both sides of the die.

In the Space Research Institute performed a vibration, thermal cycling and thermal vacuum tests of X ray detectors. During this tests have been studied the leakage current stability, polarization rate, spectroscopic and imaging performance in the working temperature range.

The current status of the X-ray detectors development and testing will be presented.

9905-234, Session PS7

An updated approach to the study of proton propagation in the eROSITA mirror system

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In this paper we review the analysis of proton transmission through the eROSITA telescope and present simulations performed with an updated version of the ray tracing code where soft (10 keV-1 MeV) protons impinging onto the entrance pupil are propagated to the focal plane following the Remizovich's scatter distribution. Laboratory measurements on eROSITA mirror samples are used to validate the model and select ad-hoc parameters

9905-235, Session PS7

The high definition x-ray imager (HDXI) instrument on the X-ray Surveyor mission concept

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By utilizing optics that couple fine angular resolution (<0.5 arcsec) with large effective area (~2.3 m^2 at 1keV), the X-ray Surveyor mission would enable exploration within a unique scientific parameter space. One of the primary soft X-ray imaging instruments being baselined for this mission concept is the High Definition X-ray Imager, HDXI. This instrument would achieve this fine angular resolution imaging over a wide field of view (22 x 22 arcmin) by using a silicon sensor array with small pixels. Silicon sensors enable large-format/small-pixel devices, radiation tolerant designs, and high quantum efficiency across the entire soft X-ray bandpass. To fully exploit the X-ray Surveyor's large collecting area (~30x Chandra) without X-ray event pile-up, the HDXI will be capable of much faster frame rates than current X-ray imagers. The planned requirements and capabilities of the HDXI will be described.

9905-236, Session PS7

Laboratory demonstration of the piezoelectric figure correction of a cylindrical slumped glass optic

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The X-ray Surveyor is a mission concept for a next generation X-ray observatory. This mission will feature roughly 30 times the effective area of the Chandra Observatory while matching its sub-arcsecond angular resolution. The key to meeting these requirements is lightweight, segmented optics. To ensure these optics achieve and maintain sub-arcsecond performance, we propose to use piezoelectric coatings for post-bonding and on-orbit figure correction. We have fabricated a cylindrical prototype optic with piezoelectric adjusters and measured its performance using optical metrology. We present the results of this laboratory figure correction and discuss their implications for an observatory featuring adjustable X-ray optics.

9905-237, Session PS7

An alignment budget for the X-Ray Surveyor telescope

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This paper presents a first proposal of an error budget for the image quality of the X-ray Surveyor (XRS) Telescope. The XRS telescope is proposed to be a Wolter-Schwarzchild prescription consisting up of many modules. The resulting budget is the set of intermodule alignment tolerances that give a specific image quality, considering both on and off axis imaging performance. The tolerance space that yields imaging performance in the sub-arcsecond class is examined for trades and sensitivities.

9905-238, Session PS7

Ray-tracing critical angle transmission gratings for the X-ray Surveyor mission

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The X-ray surveyor mission will feature a large collecting area and provide sub-arcsecond imaging resolution over a wide X-ray band. In addition to direct imaging, it will feature an X-ray grating spectrometer designed for a spectral resolving power of order 5000, significantly higher than flown on any other X-ray mission. This new technology will allow us to resolve kinematic components in absorption and emission lines of galactic and extragalactic matter down to unprecedented dispersion levels.

In this work, we study a critical angle transmission (CAT) grating spectrograph that could fulfill these design goals. We perform ray-trace simulations to characterize the performance depending on the angle of inclination between the grating and the ray and the placement of the Rowland-torus in relation to the optical axis. For each design we study the influence of finite-size effects for the grating facets and how performance degrades with increasing misalignments of the grating facets and readout CCDs.

Our newly developed ray-trace code is a tool suite to simulate the performance of X-ray observatories. It is primarily aimed at astronomical X-ray telescopes and sounding rocket payloads, but can be used to ray-trace experiments in the laboratory as well. The simulator code is written in python, because the use of a high-level scripting language allows modifications of the simulated instrument design in very few lines of code. This is especially important in the early phase of mission development, when the performances of different configurations are contrasted. To reduce the run-time and allow for simulations of a few million photons in a few minutes on a desktop computer, the simulator code uses tabulated input (from theoretical models or laboratory measurements of samples) for grating efficiencies and mirror reflectivities.

Based on these simulations we analyze strategies to improve the spectral resolution such as sub-aperturing. We define the error budget for grating facet misalignments, grating constant variations and other uncertainties that are inevitable in the manufacturing process of any instrument.

9905-239, Session PS7

A new type of multiple image x-ray interferometer for arcseconds and sub-arcsecond sources

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A new type of X-ray interferometer using an X-ray grating and an X-ray imaging spectrometer, such as X-ray CCDs or X-ray pixel detectors, is proposed. This interferometer does not employ any mirrors. Instead, multiple images (self images of the grating) generated with the Talbot effect are extracted and employed.

If we use a 5um pitch X-ray grating and X-ray with the wavelength of 0.1nm (12keV), the first self images are expected to focused at the distance of 25cm from the grating. The width of each self image corresponds to the angular size of 2 arc seconds. It means we can measure the X-ray source size of this order or smaller. One of the advantages of this methods is we only need to measure the self images of the identical profiles. We can sample the profile with X-ray detectors with lower position resolution as for moire imaging.

Although our method use similar configuration to X-ray Talbot interferometer with which phase contrast imaging of light material such as human body, and inspired by that method, different information is extracted. The X-ray Talbot interferometer measures the distortion of wave front by the sample material located in front of the grating. Our X-ray multiple image interferometer does not place the sample material, but measure the size of the X-ray source.

We consider possible improvement of the angular resolution of this system to obtain sub-arcsecond resolution, with future prospect of this method.

9905-240, Session PS7

Direct imaging of star vicinity using a miniaturized distributed occulter/telescope in Earth orbit

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Distributed occulter/telescope systems hold great promise in the field of direct exoplanet imaging. However, proposed missions using this concept such as the New Worlds Observer and Exo-S (NASA) are exceptionally large with occulter diameters of tens of meters and inter-spacecraft separations of tens of megameters, requiring deployment in deep space. These missions are characterized by exorbitant costs in the order of billions of dollars and high risk due to the low technological readiness of the involved technologies. In order to mitigate the risks associated with these missions, this paper presents new findings from optical and orbit design studies of a novel concept recently proposed by the authors, namely a Miniaturized Distributed Occulter/Telescope (mDOT) based on two micro-/nano-satellites in earth orbit. The proposed mission serves two key purposes: 1) demonstrate key technologies required by future large-scale space observatories including light suppression performance of the occulter and precise guidance, navigation, and control, and 2) detect, map, and characterize a set of scientifically valuable targets such as exozodiacal dust formations and large exoplanets. The envisioned mission includes a nano-satellite telescope of 10cm aperture separated from a micro-satellite occulter by a few hundred kilometers in earth orbit. Because detection and imaging of scientifically interesting targets requires starlight suppression of 10^?7 or better, the occulter is designed to suppress some bandwidth in the ultraviolet spectrum (150-400nm) to compensate for its limited size. Additionally, the occulter is designed such that optical performance is insensitive to separation deviations of 1%. The required observation time for a 10cm telescope in the ultraviolet spectrum is on the order of tens of hours or larger and can only be achieved with an optimal orbit design. The proposed formation design leverages the separation insensitivity to minimize the total delta-v (propellant) cost via a two-stage operations concept. The science phase is centered about the apogee of a highly elliptical orbit such as a geosynchronous transfer orbit. Here, a low-thrust, quasi-continuous control system is used to maintain decimeter-level relative position control perpendicular to the line-of-sight while the telescope images the target from within the shadow of the occulter. The formation design aligns the relative acceleration with the observation axis to minimize delta-v cost. Using this strategy, continuous observations

of over one hour without control input along the observation axis can be achieved. The reconfiguration phase takes place after each science phase and consists of a sequence of impulsive maneuvers to ensure that the formation is properly aligned at the start of the next science phase. Preliminary design results show great promise. The total delta-v cost of accumulating 10 hours of observation time is well within the capacity of current propulsion systems. The required manufacturing precision to achieve starlight suppression of 10^?7 is comparable to specifications for large-scale occulters. Finally, a preliminary system design for the telescope spacecraft suggests that a 6U CubeSat telescope spacecraft can meet key design parameters (power, data, and delta-v) with ample margins. Overall, these studies suggest that an mDOT in earth orbit is both feasible and scientifically valuable.

9905-241, Session PS7

iWF-MAXI: a soft x-ray transient monitor on the ISS

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iWF-MAXI is an X-ray transient monitor mission proposed as an experiment payload on the JEM/EF (Japanese Experiment Module Exposed Facility) of the International Space Station.

It has four main scientific goals:

(1) To find and localize the X-ray counterparts of gravitational wave events, which are expected to be detected by the next generation gravitational wave detectors such as Advance LIGO and KAGRA in late 2010's.

(2) To detect short soft X-ray transients such as stellar flares, nova ignitions, and supernova shock breakouts, and promptly notify the world.

(3) To trigger on short high-energy transients such as gamma-ray bursts and tidal disruption events, and promptly disseminate their locations to the community.

(4) To detect the onset of activities from black hole binaries, neutron star binaries, and active galactic nuclei (AGN), and issue alerts to the astronomical community of the world.

Its main scientific instrument is the Soft X-ray Large Solid Angle Camera (SLC).

It is sensitive in the energy range of 0.7–10 keV with a localization accuracy of $0.1.

It will detect short transient events like GRBs with durations from a fraction of a second to minutes that occur in its large large field of view (>10% of the entire sky).

With the orbital revolution of the ISS, iWF-MAXI scans much larger sky area in 90 minutes, and looks for slower events such as outbursts of X-ray binaries.

iWF-MAXI uses iSEEP, a medium-size multi-use bus system developed at JAXA in order to save the cost and development time. Missions on the ISS benefits from its infrastructure. The availability of real-time ground contact during 70% of the in-orbit time is particularly favorable for monitor missions that issue prompt alerts for explosive astrophysical transients. On the other hand, iWF-MAXI has to live with various constraints of the ISS/iSEEP payload, such as volume envelope, mass, power, thermal environment, radiation, and safety requirements.

In 2015, iWF-MAXI has been proposed to the small-scale project category of ISAS/JAXA, and has passed the review by the Advisory Committee for Space Science. We are currently working on the design study to accommodate the mission within theses constraints.

9905-242, Session PS7

Opportunities for the high energy astrophysics community by the AHEAD European Infrastructure Project

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AHEAD (Integrated Activities in the High Energy Astrophysics Domain) is a project approved in the framework of the European H2020 program. Its main objective is to integrate European key research infrastructures for the domain by offering free-of-cost transnational access to a wide choice of facilities. Two distinct programs aim at opening access to facilities for test and calibration of space-based sensors and optics, and to institutes or data centres for mentoring/tutorial sessions on data analysis of the best high-energy astrophysical observatories. Moreover, our visitor program provides financial support for visits of experienced scientists and engineers to scientific institutes in Europe and EU associated countries. We will discuss the expected impact in relation to the current astrophysics mission programs, along with the specific opportunities given by the second, recently opened, AO. We will also describe the first results and lessons learned from the previous call.

9905-243, Session PS7

The AHEAD Horizon 2020 Program for the high energy astrophysics domain

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The overall objective of AHEAD (Integrated Activities in the High Energy Astrophysics Domain) is to integrate national efforts in High-Energy Astrophysics, keeping its community at the cutting edge of science and technology and ensuring that space observatories are at the state of the art. AHEAD will integrate key research infrastructures including facilities for on-ground test and calibration and for data analysis of high-energy astrophysical observatories, by opening them to the space science community through its transnational access program. The technological development will focus on the improvement of selected critical technologies, background modeling, cross calibration, and feasibility studies of space-based instrumentation. Other programs include grants for collaborative studies, dissemination and public outreach and promotion of

workshops. Strong connections between institutes and industry will enable the development of new technologies and the associated market growth.

9905-269, Session PS7

Compact hard x-ray imaging system with large FOV

Miho Katsuragawa, ISAS - JAXA (Japan) and The Univ. of Tokyo (Japan); Shin'ichiro Takeda, OIST (Japan); Goro Sato, Atsushi Harayama, ISAS - JAXA (Japan); Shin Watanabe, Tadayuki Takahashi, ISAS - JAXA (Japan) and The Univ. of Tokyo (Japan)

No Abstract Available

9905-66, Session 15

Aberrations in square pore micro-channel optics used for x-ray lobster eye telescopes

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We identify all the significant aberrations that limit the performamce of square pore micro-channel plate optics (MPOs) used as an X-ray lobster eye.

These aberrations are incorporated into a comprehensive software model of the X-ray response of the optics and the predicted imaging and efficiency response is compared with the measured performance obtained from a breadboard lobster eye X-ray optic constructed for the SVOM MXT program.

The results reveal the manufacturing tolerances which limit the current performance of MPOs and enable us to identify particular intinsic aberrations which will limit the ultimate performance we can expect from MPO-lobster eye telescopes.

9905-67, Session 15

Development of the four-stage x-ray telescope (FXT) for the DIOS mission

Yasunori Babazaki, Ren Nakamichi, Ayako Bandai, Yuzuru Tawara, Ikuyuki Mitsuishi, Nagoya Univ. (Japan); Nozomi Nakaniwa, Yoshitomo Maeda, Institute of Space and Astronautical Science (Japan) and Japan Aerospace Exploration Agency (Japan)

A small satellite mission, the Diffuse Intergalactic Oxygen Surveyor (DIOS), is designed to carry out X-ray observations for detecting the warm-hot intergalactic medium (WHIM), which is a candidate of missing baryons, and revealing the large scale structure of the nearby universe (z < 0.3). In order to achieve the scientific goals, a telescope for the DIOS is required to possess high sensitivity for diffuse sources (grasp > 100 cm2 deg2 @ 0.6 keV) and an angular resolution of 5 arcmin. A Four-stage X-ray Telescope (FXT) has been developed as the best-fit optics for the DIOS mission because a four-stage optical system makes it possible to realize short focal length and large aperture at the same time.

We fabricated a third demonstration model of the FXT which consists of a quadrant housing, 3 sets of four-stage mirrors with a diameter of ~500 mm, a length of 36 mm, a thickness of 0.22 mm, and a focal length of 700 mm, and alignment plates. A new alignment system which adjusts radial positions of alignment plates is introduced. Platinum with a thickness of 1000 A was coated on the mirrors in the replication process. The FXT performance was investigated at the ISAS 30-m X-ray pencil beam facility using a monochromatic energy of 1.5 keV after tuning of radial positions of the alignment plates in optical. The best angular resolution for one set of four-stage mirrors is about 6 arcmin in HPD which is about 1 arcmin better than that of the previous samples. We confirmed that the resulting effective area is consistent with that of the expected in the ray-tracing simulation. The FXT mirrors with a focal length of 1200 mm and a diameter of 240 mm were also designed to obtain higher reflectivity at a higher energy range above 2 keV and prepared. We conducted an X-ray irradiation test also for the samples using a monochromatic energy of 4.5 keV. Consequently, the best angular resolution for one set of four-stage mirrors is ~ 5 arcmin in HPD and we confirmed that the effective area increases significantly as expected.

9905-68, Session 15

Development of x-ray multilayer telescope optics for XTP mission

Zhengxiang Shen, Xiaoqiang Wang, Kun Wang, Bin Ma, Qiushi Huang, Zhong Zhang, Tongji Univ. (China); Haifeng Wang, Donghua Univ. (China); Ying Dai, Pengfei He, Zhanshan Wang, Tongji Univ. (China)

The X-ray Timing and Polarization (XTP) satellite is dedicated to study black hole, neutron star and magnetar and then get more information in the physics under extreme gravity, density and magnetism. With an effective area of about 1 square meter and angular resolution of 1 arcminute, XTP is expected to make the most sensitive temporal and polarization observations with good energy resolution in 1-30 keV. Large collecting areas are obtained by tightly nesting layers of grazing incidence mirrors in a conical approximation Wolter-I design. The segmented mirrors that form these layers are formed by thermally slumping glass substrates coated with depth-graded W/Si multilayers for enhanced reflectivity in higher energy region. In order to force the overall shape of the nominally cylindrical substrates to the appropriate conic form, an over-constraint method was used to assemble the mirrors to a telescope. We will present performance on the XTP optics and report the current status of the telescope production.

9905-69, Session 15

Progress on the fabrication of high resolution and lightweight monocrystalline silicon x-ray mirrors

Raul E. Riveros, NASA Goddard Space Flight Ctr. (United States) and Univ. of Maryland, Baltimore County (United States); Michael P. Biskach, Kim D. Allgood, James R. Mazzarella, SGT, Inc. (United States); Marton V. Sharpe, SGT, Inc. (United States); William W. Zhang, NASA Goddard Space Flight Ctr. (United States)

Monocrystalline silicon could be an excellent X-ray mirror substrate material due to its high stiffness, low density, high thermal conductivity, zero internal stress, and commercial availability. Our work at NASA Goddard Space Flight Center focuses on identifying and developing a manufacturing process to produce high resolution and lightweight X-ray mirror segments in a cost and time effective manner. Previous

efforts focused on demonstrating the feasibility of cylindrical silicon mirror polishing and lightweighting. Present efforts are aimed towards producing true paraboloidal and hyperboloidal mirror surfaces on the lightweight silicon segments. This paper presents results from these recent investigations.

9905-70, Session 15

Gas bearing slumping and figure correction of x-ray telescope mirror substrates

Brandon D. Chalifoux, Heng Zuo, Michael D. DeTienne, Graham Wright, Ralf K. Heilmann, Mark L. Schattenburg, Massachusetts Institute of Technology (United States)

Figure correction of thin x-ray telescope mirrors may be critical for future missions that require high angular resolution and large collecting areas. One promising method of providing figure correction is to use stress generated via ion implantation. Since stress-based figure correction strategies cannot correct high spatial frequency errors, it is critical to obtain glass with only low spatial frequency error. One method is thermal gas bearing slumping, where glass is softened while floating on thin films of gas. This method avoids introducing mid- or high- spatial frequency errors by eliminating contact between the glass and mandrel. Together, our methods are a promising approach to fabricating mirrors for a high angular resolution, large-area x-ray observatory. In this paper we report on progress in advancing the air bearing slumping to higher gas pressures and curved geometry. We also report on continued progress on advancing the ion implantation technology toward correcting flight-sized mirror substrates.

9905-71, Session 15

Slumped glass optics development with pressure assistance

Bianca Salmaso, Stefano Basso, Marta M. Civitani, Mauro Ghigo, Joanna Holyszko, Daniele Spiga, Gabriele Vecchi, Giovanni Pareschi, INAF - Osservatorio Astronomico di Brera (Italy)

Thin glass mirrors are a viable solution to build future X-ray telescopes with high angular resolution and large collecting area. This approach is very attractive for the optics implementation of future X-ray astronomy projects like the X-ray Surveyor Missions in USA, the XTP mission in China and the NGHXT mission in Japan (all this projects could have an European participation). In the case of the X-ray Surveyor Mission, where a sub-arcsec angular resolution is requested, the use of actuators or post correction with sputtering deposition is envisaged. The hot slumping assisted by pressure is an innovative technology developed in our laboratories to replicate a mould figure. Our hot slumping process is based on thin substrates of Eagle XG glass to be thermally formed on Zerodur K20 moulds. This technology is coupled with an integration process able to damp low frequency errors. A continuous improvement in the reduction of the mid-frequency errors led to slumped glass foils with a potential angular resolution evaluated from the metrological data of a few arcsec, HEW. High frequency errors have been for a long time a critical point of our technology. In particular, the pressure assistance was leading to a partial replication of the mould micro-roughness, causing a quite relevant contribution to the PSF of a few arcsec (depending on the incidence angle and photon energy). Therefore, we developed a new process to further reduce the micro-roughness of slumped glass foils, making the technology now attractive for telescopes sensitive also in the hard X-tray band. This paper provides the latest status of our research.

9905-72, Session 15

New lithographic techniques for x-ray spectroscopy

Jake A. McCoy, Casey T. DeRoo, Randall L. McEntaffer, The Univ. of Iowa (United States)

X-ray spectroscopy has been proven to be an extremely important aspect of high energy astrophysics. In addition to providing a powerful tool for performing diagnostics in astrophysical plasmas, high-resolution X-ray spectroscopy has direct applications to several key scientific issues including making measurements of the warm-hot intergalactic medium, determining elemental abundances in the local interstellar medium and studying dynamics in active galactic nuclei. The majority of astrophysically abundant X-ray spectral lines exist below 2 keV, at soft X-ray energies, necessitating the use of diffraction gratings to perform high-resolution spectroscopy. The grating spectrometers on board XMM-Newton and the Chandra X-ray Observatory have resolving powers on the order of several hundred and have provided large amounts of scientific return. Future X-ray observatories will require advanced spectrometers with resolving powers of a few thousand to make significant improvements in X-ray spectroscopy and to address future scientific problems. Reflection gratings can be integrated into a grazing incidence optical system of an X-ray telescope by being positioned to intercept the radiation coming to a focus. When compared to the standard in-plane geometry of reflection gratings, the off-plane design has several attractive features. First, there is minimal groove shadowing at grazing incidence angles resulting in high diffraction efficiency. In addition, off-plane gratings feature lower scatter, have better spectral coverage than in-plane gratings, and have the potential for high resolving power. Further, off-plane gratings can be tightly packed into an array, offering an efficient way for them to be paired with Wolter-I optics in an X-ray telescope. To maximize spectral resolution and diffraction efficiency, these gratings must feature a high-precision custom groove profile. Gratings with parallel grooves lead to aberrations when dispersing a spectrum from a converging beam of radiation. To remedy this, these gratings must be radially ruled such that groove density increases in the direction that radiation travels to the focal plane of the telescope. Further, gratings with groove facets blazed to a triangular saw-tooth profile will preferentially disperse X-rays to one side of zero order, effectively doubling signal-to-noise in the detected spectrum with half the number of necessary detector elements. As a result, the development of radially ruled off-plane gratings, with high groove densities and blazed groove facets, that can be compactly stacked and aligned in array will be critical to push the state-of-the-art for instruments in the future. This paper describes the development of a novel fabrication method to produce these gratings using techniques in electron-beam lithography (EBL) and presents preliminary results. In this approach, approximating the idealized radially ruled groove profile to high fidelity requires the use of an EBL tool with a sufficiently small minimum step size. Further, producing blazed groove facets requires carefully controlling e-beam doses to create multilevel staircase structures in the resist and using thermal reflow to smooth them to inclines.

9905-73, Session 16

ATHENA: the advanced telescope for high energy astrophysics *(Invited Paper)*

Kirpal Nandra, Max-Planck-Institut für extraterrestrische Physik (Germany)

Athena is the next generation X-ray astronomy facility, currently under Phase A study by the European Space Agency for a launch in 2028. The scientific objectives and current status of the Athena project will be reviewed, as well as the activities of the Athena Science Study study team and the scientific community that supports the mission.

9905-74, Session 16

ATHENA: system studies and optics accommodation

Mark R. Ayre, Marcos Bavdaz, Ivo Ferreira, Eric Wille, Sebastiaan Fransen, Alexander Stefanescu, Martin Linder, European Space Research and Technology Ctr. (Netherlands)

ATHENA is currently in Phase A, with a view to formal adoption upon a successful System Requirements Review in 2019. After a brief presentation of the reference spacecraft design, this paper will focus on the functional and environmental requirements, the thermo-mechanical design and the Assembly, Integration & Test (AIT) considerations related to the very large Mirror Assembly Module (MAM) housing the Silicon Pore Optics (SPO).

Initially functional requirements on the optics accommodation are presented, with the Effective Area and Half Energy Width (HEW) requirements leading to a MAM comprising (depending on final mirror size selected) between ~700-1000 Mirror Modules (MM), co-aligned with exquisite accuracy to provide a common focus. A preliminary HEW budget allocated across the main contributors is presented, and this is then used as a reference to derive subsequent requirements and engineering considerations, including: The procedures and technologies under consideration for AIT to achieve the required alignment; stiffness requirements and handling scheme required to constrain deformation under gravity during x-ray testing; temperature control to constrain thermo-elastic deformation during flight; and the capability to focus using the Instrument Switching Mechanism (ISM).

Next, our best understanding of the launch mechanical environment imposed by the forthcoming Ariane-64 launch vehicle is presented along with the mechanical requirements of the MMs, and the need to minimise shock-loading of the MMs is stressed. Methods to achieve this are presented, including: Modal-tuning of the MAM to act as a low-pass filter during launch shock events; the possibility to deploy a passive vibration solution in the launcher interface plane to reduce loads.

9905-75, Session 16

The ATHENA optics development

Marcos Bavdaz, Eric Wille, Brian Shortt, Sebastiaan Fransen, European Space Agency (Netherlands); Maximilien J. Collon, Nicolas M. Barrière, cosine B.V. (Netherlands); Alexei Yanson, Giuseppe Vacanti, cosine Science & Computing B.V. (Netherlands); Jeroen Haneveld, Micronit Microfluidics B.V. (Netherlands); Coen van Baren, SRON Netherlands Institute for Space Research (Netherlands); Karl-Heinz Zuknik, OHB AG (Germany); Finn E. Christensen, DTU Space (Denmark); Michael Krumrey, Physikalisch-Technische Bundesanstalt (Germany); Vadim Burwitz, Max-Planck-Institut für extraterrestrische Physik (Germany); Giovanni Pareschi, Daniele Spiga, INAF - Osservatorio Astronomico di Brera (Italy); Giuseppe Valsecchi, Media Lario Technologies S.r.l. (Italy); Dervis Vernani, RUAG Space AG (Switzerland)

ATHENA (Advanced Telescope for High ENergy Astrophysics) is being studied by the European Space Agency (ESA) as the second large science mission, with a launch slot in 2028. System studies and technology preparation activities are on-going.

The optics of the telescope is based on the modular Silicon Pore Optics (SPO), a novel X-ray optics technology significantly benefiting from spin-in from the semiconductor industry. Several technology development activities are being implemented by ESA in collaboration with European industry and institutions. The related programmatic background, the status of the SPO technology and the associated planning will be presented in the paper.

9905-76, Session 16

Silicon pore optics for the ATHENA telescope

Maximilien J. Collon, Giuseppe Vacanti, Ramses Günther, Alexei Yanson, Nicolas M. Barrière, Boris Landgraf, Mark Vervest, Abdelhakim Chatbi, Marco W. Beijersbergen, cosine B.V. (Netherlands); Marcos Bavdaz, European Space Agency (Netherlands); Eric Wille, European Space Research and Technology Ctr. (Netherlands); Jeroen Haneveld, Arenda Koelewijn, Micronit Microfluidics B.V. (Netherlands); Coen van Baren, SRON Netherlands Institute for Space Research (Netherlands); Peter Müller, Michael Krumrey, Physikalisch-Technische Bundesanstalt (Germany); Vadim Burwitzz, Max-Planck-Institut für extraterrestrische Physik (Germany); Marta M. Civitani, INAF - Osservatorio Astronomico di Brera (Italy); Daniele Spiga, Giovanni Pareschi, Istituto Nazionale di Astrofisica (Italy); Sonny Massahi, Finn E. Christensen, DTU Space (Denmark); Giuseppe Valsecchi, Media Lario Technologies S.r.l. (Italy)

Silicon Pore Optics is a high-energy optics technology, invented to enable the next generation of high-resolution, large area, X-ray telescopes such as the ATHENA observatory, an European large (L) class mission with a launch date of 2028. The technology development is carried out by a consortium of industrial and academic partners and focuses on building an optic with a focal length of 12 m that shall achieve an angular resolution better than 5". So far we have built optcs with with a focal length of 50 m and 20 m.

This paper presents details of the work carried out to build silicon stacks for a 12 m optic and to integrate them into mirror modules. It will also present results of x-ray tests taking place at the BESSY synchrotron and the PANTER test facility.

9905-77, Session 16

Mass production of silicon pore optics for ATHENA

Eric Wille, Marcos Bavdaz, European Space Agency (Netherlands); Maximilien J. Collon, cosine B.V. (Netherlands)

Silicon Pore Optics (SPO) provide high angular resolution with low effective area density as required for the Advanced Telescope for High Energy Astrophysics (ATHENA). The x-ray telescope consists of several hundreds of SPO mirror modules. During the development of the process steps of the SPO technology, specific requirements of a future mass production have been considered right from the beginning. The manufacturing methods heavily utilise off-the-shelf equipment from the semiconductor industry, robotic automation and parallel processing. This allows to upscale the present production flow in a cost effective way, to produce hundreds of mirror modules per year.

Considering manufacturing predictions based on the current technology status, we present an analysis of the time and resources required for the ATHENA flight programme. This includes the full production process starting with Si wafers up to the integration of the mirror modules. We present the times required for the individual process steps and identify the equipment required to produce two mirror modules per day. A preliminary timeline for building and commissioning the required infrastructure, and for flight model production of about 1000 mirror modules, is presented.

9905-166, Session PS5

Observing the WHIM with ATHENA

Jörn Wilms, Thorsten Brand, Thomas Dauser, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Philippe Peille, Institut de Recherche en Astrophysique et Planétologie (France); Beatriz Cobo, Maite Ceballos, Univ. de Cantabria (Spain); Jelle S. Kaastra, SRON Netherlands Institute for Space Research (Netherlands); Paul O'Brien, Univ. of Leicester (United Kingdom); Xavier Barcons, Univ. de Cantabria (Spain); Luigi Piro, INAF - Istituto di Astrofisica e Planetologia Spaziali (Italy); Jan-Willem A. den Herder, SRON Netherlands Institute for Space Research (Netherlands); Didier Barret, Institut de Recherche en Astrophysique et Planétologie (France)

We present the results of simulations of the detection probability for absorption lines from ions in the warm and hot ionized medium with ATHENA in the spectra of Gamma-ray burst afterglows. Performed using the end to end simulation framework SIXTE, the simulations are based on Swift XRT lightcurves of afterglows. We simulate both the case of single and multiple lines, as well as results for line searches in absorption structures from a more complex medium.

9905-167, Session PS5

Detectability of exoplanet transits with ATHENA's WFI instrument: testing for white and correlated noise

Stefania Carpano, Max-Planck-Institut für extraterrestrische Physik (Germany); Jörn Wilms, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Arne Rau, Max-Planck-Institut für extraterrestrische Physik (Germany)

One of the science goals of the Athena X-ray observatory is to detect and characterize the X-ray transits of hot Jupiter-like planets orbiting their parent stars. To date, the only suitable source for these studies is HD 189733b, a Jupiter-size planet in a 2 d orbit, for which a transit depth of 6-8% has been found from the accumulation of several Chandra and XMM-Newton observations.

Here, we simulate realistic light curves of exoplanet transits using the SIXTE Athena end-to-end simulator and derive the expected signal-to-noise ratio (SNR) for different configurations of the Wide Field Imager (WFI) instrument and for different planetary system parameters. We first generate flat light curves for different source fluxes to derive the (white noise) standard deviation. Next, moderate level of correlated noise and transits of different depths are added to the light curves.

For pure white noise, the SNR is proportional to the square root of the flux, of the light curve bin size and of the number of co-added transits, and by definition proportional to the transit depth. When correlated noise starts to be significant, re- binning the data will only slightly increase the SNR, depending on the noise characteristics. Considering only white noise, a transit from a source like HD 189733, with a source flux around 5e-13 erg s^-1 cm^-2 and a transit depth of about 5% can be detected with a SNR>3 in a unique transit with Athena. With correlated noise, stacking of the observations of multiple transits may be necessary.

9905-168, Session PS5

Silicon pore optics mirror module assembly method

Nicolas M. Barrière, Abdelhakim Chatbi, Maximillien J. Collon, Ramses Günther, Boris Landgraf, Giuseppe Vacanti, Roy van der Hoeven, Mark Vervest, Alexei Yanson, cosine B.V. (Netherlands); Marcos Bavdaz, Eric Wille, European Space Agency (Netherlands)

Silicon Pore Optics are produced as stacks of mirror plates, which are then paired to form X-ray Optics Units (XOUs). For Athena, in the current scheme, two XOUs are glued together in between a set of brackets, leading to mirror modules made of 4 stacks. Mirror modules are integrated at the XPBF beamline of PTB (BESSY synchrotron, Berlin), using a pencil X-ray beam; The relative orientation of the secondary stack with respect to the primary stack is fitted using the positions of the reflected beamspots onto the camera. This provides a deterministic way of orienting stacks with respect to each other within a XOU, and allows meeting with the stringent angular accuracy requirements. The same operation is then repeated for the second XOU composing a mirror module, with the additional constraint that it needs to be confocal with the first one. In this talk we review the method that is used to integrate stacks into mirror modules.

9905-169, Session PS5

Predicting silicon pore optics

Giuseppe Vacanti, Nicolas M. Barrière, Abdelhakim Chatbi, Ramses Günther, cosine Science & Computing B.V. (Netherlands); Maximilien J. Collon, cosine B.V. (Netherlands); Roy van der Hoeven, Boris Landgraf, Mark Vervest, Alexei Yanson, cosine Science & Computing B.V. (Netherlands); Marcos Bavdaz, Eric Wille, European Space Research and Technology Ctr. (Netherlands)

While X-ray characterization of Silicon Pore Optics provides the ultimate validation of their performance, modelling and simulation also have an important role in the development efforts. We report on the latest results on this front, and in particular on the developments aiming at making the models understand possibly every piece of metrology available during the production process. Besides understanding how the optics behave, this effort also aims at being able to assess the X-ray performance of stacks without making use of actual X-ray measurements.

9905-170, Session PS5

Characterizing silicon pore optics stacks

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Every Silicon Pore Optics stack made is characterized at the PTB's X-ray Pencil Beam Facility (BESSYII). We describe how the stacks are measured, and the data analyzed by means of an automatic analysis pipeline. The pipeline can be run in live mode, while the measurement is is progress, so that a few minutes after completion a complete characterization is available. This provides immediate feedback on the quality of the stacks and comparison with the available metrology.

9905-171, Session PS5

X-ray mirror coating design, development, and testing for the ATHENA mission

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We present results on X-ray mirror coating optimisation based on the latest optics geometry adopted for ATHENA along with the development and testing of coatings on silicon pore optics (SPO) substrates.

This study include pre and post coating characterisation of the x-ray mirrors using Atomic Force Microscopy (AFM), X-ray reflectometry (XRR) and scatter measurements performed at the 8 keV X-ray facility at DTU Space and with synchrotron radiation in the laboratory of PTB at BESSY II.

We report our findings on surface roughness, coating reflectivity, environmental tests and long term stability of coatings considering the grazing incidence angles and energies of ATHENA.

9905-172, Session PS5

Upgrades to the PANTER x-ray test facility for future missions

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Activities at the Max-Planck-Institute for extrateréstial Physics PANTER X-ray test facility to develop and test X-ray optics and telescopes for new missions will be described. Currently upgrades to the test facility are beeing made to allow detailed thermo-optical studies of X-ray optics in the X-ray beamline, especially for baseline Silicon Pore Optics for the ATHENA and ARCUS missions. Also the accomodation in the test facility of the large up to 3 m diameter ATHENA optic is beeing studied. Furthermore plans for tests of the soft X-ray telescope for the SVOM mission, the XIPE

X-ray polarimetry telescope will be presented.

9905-173, Session PS5

Measuring SPOs at the PANTER x-ray test facility: the alignment

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The development and calibration of silicon pore optics (SPOs) as proposed for ATHENA is supported by continuous measurements at the PANTER X-ray test facility.

To obtain comparable measurement results for the SPOs robust alignment procedures are needed to place the mirror module with respect to the optical axis.

In this work we examine, how the angular resolution and the effective area of the SPOs are influenced by the alignment.

By means of ray tracing simulations and X-ray measurements the influence of the alignment is investigated.

Based on these results it is demonstrated how the characteristics of these influences can be used to align the SPOs at the PANTER X-ray test facility.

9905-174, Session PS5

New x-ray pencil beam facility for the characterization of silicon pore optics

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A new X-ray pencil beam facility (XPBF 2.0) has been installed in the laboratory of the Physikalisch-Technische Bundesanstalt at the synchrotron radiation facility BESSY II in Berlin to characterize silicon pore optics (SPOs) for the future X-ray observatory ATHENA. As the existing XPBF which is operated since 2005, the new beamline provides a pencil beam of very low divergence, a vacuum chamber with a hexapod system for accurate positioning of the SPO to be investigated, and a vertically movable CCD-based camera system to register the direct and the reflected beam. In contrast to the existing beamline, a multilayer-coated toroidal mirror is used for beam monochromatization and collimation, enabling the use of beam diameters between about 100 μm and several mm at a photon energy of 1.6 keV. The new beamline features increased travel ranges for the hexapod to cope with larger SPOs and a sample to detector distance of 12 m corresponding to the envisaged focal length of ATHENA.

9905-175, Session PS5

Advancement status of the Beam Expanded Testing X-ray facility (BEaTriX)

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We report the advancement of the realization of the BEaTriX (Beam Expander Testing X-ray facility) project, an X-ray apparatus to generate an expanded (200x60 mm2), uniform and low divergent (~1.5 arcsec HEW) soft X-ray beam within a small lab (6x15 m2). BEaTriX will be used to directly perform the quality control of focusing modules of large X-ray optics such as those for the ATHENA X-ray observatory, based on either Silicon Pore Optics (baseline) or Slumped Glass Optics (alternative). Given the large number of modules to be integrated (>1000) and the stringent requirement of 5 arcsec in the final angular resolution of the telescope, an even larger number of modules has to be produced and tested in series, without relying on outer metrology tools or large X-ray facilities such as synchrotron light sources. BEaTriX is being built at INAF/OAB, but due to its small size it can be replicated at the industrial site where the mirror modules will be manufactured, with the additional possibility of aligning the parabolic and the hyperbolic segments directly in X-ray illumination. The basic requirement is a beam with divergence below 1-2 arcsec HEW to characterize mirror modules that have to reach an angular resolution of about 3-4 arcsec HEW. In this paper we report design of the facility and the ongoing fabrication of the optical components including: a microfocus X-ray source, a grazing incidence paraboloidal mirror to parallelize the beam, a crystal monochromation system, and an asymmetrically-cut diffracting crystal used to perform the beam expansion to the desired size. A detailed performance simulation of the system is also shown.

9905-176, Session PS5

Simulation and modeling of silicon pore optics for the ATHENA x-ray telescope

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The ATHENA X-ray observatory is a large-class ESA approved mission, with launch scheduled in 2028. The technology of Silicon Pore Optics (SPO) was been selected as the baseline to assemble ATHENA's optic with more than 1000 mirror modules, obtained by stacking wedged and ribbed silicon wafer plates onto silicon mandrels to form the Wolter-I configuration. Even if the current baseline design fulfills the required effective area of 2 m2 at 1 keV on-axis, alternative design solutions, e.g., privileging the field of view or the off-axis angular resolution, are also possible. Moreover, the stringent requirement of a 5 arcsec HEW angular resolution at 1 keV entails very small profile errors and excellent surface smoothness, as well as a precise alignment of the 1000 mirror modules to avoid imaging degradation and effective area loss. Finally, the stray light issue has to be kept under control. In this paper we show the preliminary results of simulations of optical systems based on SPO for the ATHENA X-ray telescope, from pore to telescope level, carried out at INAF/OAB and DTU Space under ESA contract. We show ray-tracing results, including assessment of the misalignments of mirror modules, the impact of stray light, for different optical configurations and assuming realistic mirror imperfections. We also deal with a detailed description of diffractive effects expected in an SPO module from UV light, where the aperture diffraction prevails, to X-rays where the surface diffraction plays a major role. Finally, we perform a comparison of some predictions with the X-ray calibration tests performed at the BESSY synchrotron and suggest possible improvement of the baseline design.

9905-177, Session PS5

Development and production of a multilayer-coated x-ray reflecting stack of silicon pore optics for the ATHENA mission

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The Advanced Telescope for High-Energy Astrophysics, ATHENA, selected as the European Space Agency's second large-mission, is based on the novel Silicon Pore Optics technology.

DTU Space has been working for several years on the development of multilayer coatings on the Silicon Pore Optics in an effort to optimize the throughput of the Athena optics. A linearly graded Ir/B4C multilayer has been deposited on the mirrors, via the direct current magnetron sputtering technique, at DTU Space. This specific multilayer has, through simulations, proven to give the highest reflectivity at 6 keV, which is a goal for the scientific objectives of the mission.

A critical aspect of the coating process concerns the use of photolithography techniques upon which we will present the most recent developments in particular related to the cleanliness of the plates.

Experiments regarding the lift-off and stacking of the mirrors have been performed and the results attained will be presented.

9905-178, Session PS5

Implementation and fabrication considerations of an optimal hybrid array for the ATHENA x-ray integral field unit instrument

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Options for the design of the Athena X-IFU microcalorimeter that employ more than one type of pixel have a number of advantages but also present challenges. In this presentation, we present these advantages and challenges, how they trade off against each other from a technical perspective, and the progress made so far towards minimizing the challenges. In this paper we will discuss the technical implications of developing a hybrid array, and describe our progress to date in the development of these arrays. In particular we consider the implications of developing a hybrid array consisting of a small pixel array (SPA) at the center of a focal plane detector, where here small means that the pixel pitch is 75 to 120 microns. Surrounding the SPA is a large pixel array (LPA) where here large means a pitch of 250 to 300 microns. Both the SPA and LPA consist of close-packed X-ray microcalorimeters, where the temperature sensor is assumed to a transition-edge sensor (TES). There are a number of implications to consider when integrating SPA and LPA pixels within a hybrid array. While there will be serious impacts to a large number of instrument subsystems, including the electronics in the read-out and the signal processing, in this paper here we focus on the implications to fabrication and general testing.

In this paper our discussion of the implications will include the following topics:

(i) The TES transition temperature (Tc) of the bilayer for the SPA pixels may need to be different to the Tc for the LPA pixels, and each Tc will need to be adequately controlled.

(ii) The absorber composition desired for the SPA may well need to be different to that for the LPA, in terms of layer metals and thicknesses. We discuss the effect on the development of more complex processing steps such as the ion-milling of different absorber types.

(iii) The process needed to heat-sink the SPA is very different to that of the LPA pixels, and the two types of heat-sinking need to be integrated.

(iv) The routing of wires to all the pixels within the array and from the array to the transformer coils requires a slightly different routing algorithm.

(v) Pre-flight and in-flight calibration is more time-consuming and perhaps more challenging when there are two pixel types instead of one.

We will present recent progress we have made in demonstrating our ability to fabricate and develop hybrid arrays.

9905-179, Session PS5

Optimising the multiplex factor of the frequency domain multiplexed readout of the TES-based microcalorimeter imaging array for the X-IFU instrument on the ATHENA x-ray observatory

Jan van der Kuur, Luciano Gottardi, Hiroki Akamatsu, Roland H. den Hartog, SRON Netherlands Institute for Space Research (Netherlands); Mikko Kiviranta, VTT Technical Research Ctr. of Finland Ltd. (Finland); Brian D. Jackson, SRON Netherlands Institute for Space Research (Netherlands)

Athena is a space-based X-ray observatory intended for exploration of the hot and energetic universe.

One of the science instruments on Athena will be the X-ray Integrated Field Unit (X-IFU), which is a cryogenic X-ray spectrometer, based on a large cryogenic imaging array of Transition Edge Sensors (TES) based microcalorimeters operating at a temperature of 100mK. The imaging array consists of ±3800 pixels providing 2.5 eV spectral resolution, and covers a field of view with a diameter of of 5 arc minutes.

Multiplexed readout of the cryogenic microcalorimeter array is essential to comply with the cooling power and complexity constraints on a space craft. Frequency domain multiplexing has been under development for the readout of TES-based detectors for this purpose, not only for the X-IFU detector arrays but also for TES-based bolometer arrays for the Safari instrument of the Japanese SPICA observatory.

This paper discusses the design considerations which are applicable to optimise the multiplex factor within the boundary conditions as set by the space craft. More specifically, the interplay between the science requirements such as pixel dynamic range, pixel speed, and cross talk, and the space craft requirements such as the power dissipation budget, available bandwidth, and electromagnetic compatibility will be discussed. The status of the experiments which are aimed at demonstrating the baselined multiplex factor of 40, as well as options under study to increase the multiplex factor further, will be shown.

9905-180, Session PS5

Development of frequency domain multiplexing for the x-ray integral field unit (X-IFU) on the ATHENA

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We are developing the frequency domain multiplexing (FDM) read-out of transition-edge sensor (TES) microcalorimeters for the X-ray Integral Field Unit (X-IFU) instrument on board of the future European X-Ray observatory Athena. The X-IFU instrument consists of an array of sim3840 TESs with a high quantum efficiency (>90 %) and spectral resolution $Delta E$=2.5 eV @ 7 keV ($E/DeltaEsim$2800).

FDM is currently the baseline readout system for the X-IFU instrument. In FDM, TESs are coupled to a passive LC filter and biased with alternating current (AC bias) at MHz frequencies. Each resonator should be separated beyond their detector thermal response (<50 kHz) to avoid crosstalk between neighboring resonators. To satisfy the requirement of the X-IFU, a multiplexing factor of 40 pixels/channel in a frequency range from 1 to 5MHz required.

Using high quality factor LC filters and room temperature electronics developed at SRON and low-noise two stage SQUID amplifiers provided by VTT, we have recently demonstrated good performance with the FDM readout of Mo/Au TES calorimeters with Au/Bi absorbers. We have achieved X-ray energy resolutions better than 2.8 eV at frequencies between 1.3 and 3.7 MHz in the single pixel read-out. We have also shown for the first time an X-ray energy resolution better than 3 eV in a 2 pixel FDM read-out demonstration. Recently an integrated noise equivalent power resolution of about 2.0 eV at 1.7 MHz has been demonstrated with a pixel from a new TES array.

In this paper we report on the single pixel performance of these microcalorimeters under MHz AC bias, and further results of the performance of these pixels under FDM.

9905-181, Session PS5

The impact of crosstalk in the ATHENA/X-IFU instrument on the GRB/WHIM science case

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The Athena X-ray mission was selected as the second L-class mission in ESA's Cosmic Vision 2015–25 plan, with a launch foreseen in 2028, to address the theme ''Hot and Energetic Universe". One of the science cases that will be addressed by this mission is that of the missing baryons. Roughly half of the baryonic content of the Universe is suspected to be locked up in the Warm / Hot Integalactic Medium (WHIM), and detectable as OVII and OVIII absorption lines against the 0.2 - 1 keV X-ray part of spectra from distant, bright Gamma-Ray Bursts (GRBs).

One of the two instruments on board of Athena is the X-ray Integral Field Unit (X-IFU) which is based on an array of ~3800 Transition Edge Sensors (TES's) operated at a temperature of 50 mK. This science case poses an interesting challenge for this instrument, as it requires a combination of high energy resolution (better than 2.5 eV) and high countrate (several tens of counts per second per detector for GRBs as bright as 10 mCrab).

This performance on single sensor level has been demonstrated, but the operation of such detectors in an array, using multiplexed readout, brings additional challenges, both for the design of the array in which the sensors are placed and for the readout of the sensors. The readout of the

detector array will be based on Frequency Domain Multiplexing (FDM). In this system of detectors and readout, crosstalk can arise through various mechanisms: On the array, neighboring sensors can couple through thermal crosstalk. Detectors adjacent in carrier frequency may suffer from electrical crosstalk due to the finite width of the bandpass filters, and shared sources of impedance in their readout lines. The signals from the individual detectors are summed and then amplified by a pair of SQUID amplifiers before being sent to warm front-end electronics. These SQUID amplifiers exhibit a degree of non-linearity, which will give rise to higher harmonics of carriers and intermodulation products when multiple signal pulses are simultaneously present. Under high countrate conditions this is another source of crosstalk. The effect of all these crosstalk sources is that in the record of a signal pulse parasitic pulses will appear which will create a stochastic offset of the measured energy and thus a degradation of the energy resolution.

We have developed an advanced end-to-end simulator for Athena, SIXTE, with which the signals on individual detectors in an array can be simulated for various science cases. Simulated observations of WHIM absorption lines against spectra of GRBs already indicated that WHIM detections are challenging but feasible. Adding now one by one the effects of the crosstalk sources to these simulated photon streams will allow us to assess their impact on the science results, and to derive crucial information about the design of the readout chain. This will influence the choices for the wiring routing, the multiplexing factor, the number of readout chains needed, and the design and operation of the SQUID amplifiers.

9905-182, Session PS5

Gain stability with no-feedback-loop developed for the X-IFU/ATHENA readout chain

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The focal plane of the X-ray Integral Field Unit (X-IFU) instrument of the Athena observatory is composed of about 4000 micro-calorimeters. These sensors, based on superconducting Transition Edge Sensors (TES), are readout through a frequency multiplexer and a BaseBand Feedback to linearize SQUIDs. However, the loop gain of this feedback is limited to about 10, which is not enough to fix the gain of the full readout chain. Indeed, calibration of the instrument is planned to be done at a time scale larger than 10 min and the challenging energy resolution goal of 2.5 eV at 6 keV will probably requires a gain stability better than 1/100000 over this period. A large part of this gain is provided by a low-noise amplifier in the Warm Front-End Electronic (WFEE). To reach such gain stability over tens of minutes, this non-cooled amplifier has to fight against the temperature and supply voltage variations. Moreover, mainly for noise reasons, standard large loop gain feedback can't be used. We propose a new amplifier topology using diodes as loads of a differential trans-admittance amplifier to provide a fixed voltage gain, independent to the temperature and to the biasing fluctuations. This amplifier is designed using a 350 nm SiGe BiCMOS technology and is part of an integrated circuit developed for the WFEE. Simulations already highlight stability and noise performances of such structures. Comparison with standard differential structures and feedback amplifier clearly shows the advantages of the proposed amplifier topology. Performances of this diodes load trans-admittance amplifier will be discussed in the context of the X-IFU requirements.

9905-183, Session PS5

Microcalorimeter pulse analysis by means of principle component decomposition

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The X-ray integral field unit (X-IFU) for the Athena mission consists of a microcalorimeter, transition edge sensor (TES) pixel array. Incoming photons will generate pulses which have to be analyzed in terms of the energy, in order to compute the incoming X-ray spectrum.

Usually this is done by means of optimal filtering or time-domain pulse fitting.

In this paper we use an alternate way of processing by means of principle component analysis (PCA).

PCA attempts to find the main components of an orthogonal set of functions which describe the data.

We search for those components which correspond to the energy of the photons. We apply this method to TES readout by means of Frequency Domain Multiplexing (FDM).

We show, based on simulations and real data, what components are found and to what physical parameters they correspond to. We'll discuss the usefulness of this method for microcalorimeter spectral analysis and compare with other work done in this field.

9905-184, Session PS5

Performance assessment of different pulse reconstruction algorithms for the ATHENA: an x-ray integral field unit

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The X-ray Integral Field Unit (X-IFU) microcalorimeter, on-board Athena, with its focal plane comprising ~ 3800 Transition Edge Sensors (TESs) operating at 90 mK, will provide unprecedented spectral-imaging capability in the 0.2-12 keV energy range. It will rely on the on-board digital processing of current pulses induced by the heat deposited in the TES absorber, as to recover the energy of each individual events. Assessing the capabilities of the pulse reconstruction is required to understand the overall scientific performance of the X-IFU, notably in terms of energy resolution degradation with both increasing energies and count rates. Using synthetic data streams generated by the X-IFU End-to-End simulator, we present here a comprehensive benchmark of various pulse reconstruction techniques, ranging from standard optimal filtering to

more advanced algorithms based on differential geometry or principal component analysis. Beside deriving the spectral resolution achieved by the different algorithms, a first assessment of the computing power and ground calibration needs is presented. Finally, our study is applied to assess the performance of different TES-array configurations that are considered for the X-IFU, with a focus on their achievable count rate capability.

9905-185, Session PS5

The cryogenic anti-coincidence detector for ATHENA X-IFU: preliminary test and data analysis of the new bridges-suspended single pixel

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The ATHENA observatory is the second large-class mission in ESA Cosmic Vision 2015-2025, with a launch foreseen in 2028 towards the L2 orbit. The mission addresses the science theme "The Hot and Energetic Universe", by coupling a high-performance X-ray Telescope with two complementary focal-plane instruments. One of these is the X-ray Integral Field Unit (X-IFU): it is a TES based kilo-pixel order array able to provide spatially resolved high-resolution spectroscopy (2.5 eV at 6 keV) over a 5 arcmin FoV.

The X-IFU sensitivity is degraded by the particles background expected at L2 orbit, which is induced by primary protons of both galactic and solar origin, and by secondary electrons. To reduce the background level and enable the mission's science goals, a Cryogenic Anticoincidence (CryoAC) detector is placed < 1 mm below the TES array. It is a 4-pixel TES based detector, with wide Silicon absorbers sensed by Ir:Au TESes.

The CryoAC development schedule foresees as first step in 2016 the design, development and test of a new single pixel prototype featured by an absorber that is "bridges-suspended" with respect to a Silicon rim, the latter connected to a metallic frame representing the thermal bath of the microcalorimeter. These bridges are at present the best solution we have in mind to realize a well-defined and reproducible thermal conductance between the bath and the wide area absorber. This is necessary to speed up the detector and so to guarantee the high rejection efficiency of background particles imposed by mission requirements.

Here we will discuss the preliminary testing activity and data analysis of this detector, 1 cm^2 absorber area sensed by 65 Ir TESes. We will focus on the pulses analysis to understand how the TES network works in collecting the athermals phonons, which we use as fast anticoincidence flag. Furthermore, we will investigate both time-dynamic and threshold energy of the detector.

9905-186, Session PS5

The mechanical and EM simulations of the CryoAC DM for the ATHENA X-IFU

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The Demonstration Model (DM) prototype of the X-IFU Cryogenic AntiCoincidence (CryoAC) is based on a silicon monolithic micro-bridged single pixel with an active area of about 1cm2. To design such a detector, in order to fulfil the requirements, a combination of original solutions is needed: (1) fast rise times by means of the collection of fast a-thermal primary phonons; (2) a large area/thickness aspect ratio of about 30 to 50 cm; (3) about one hundred uniformly surface-distributed small superconducting transition edge sensors (TES) with highly equalized operating characteristics; (4) properly-tuned operating temperatures and dynamic range for full signal formation at the X-IFU base temperature; (5) mechanical compatibility for the flight transfer into orbit; (6) EM and thermal compatibility with the TES microcalorimeter array.

Concerning the first four issues, we have successfully achieved good results by testing several prototypes, while we kept simulating different manufacturing solutions to address the latter.

We have started the second phase in which all these detector characteristics will be combined in a single silicon monolithic micro-bridged pixel. The full set of thermal, mechanical and EM requirements have been included in a new design. We are performing several simulations with CREO and COMSOL codes in order to set the design and fabrication processes to reach the settled requirements at the level of the DM. The peculiar structure, consisting of a silicon chip asymmetrically suspended by 4 bridges, needs to be carefully studied under mechanical stresses: the response to acceleration frequency domain spectra, shocks and time domain random displacement vibrations has been evaluated in preparation for a real vibration test campaign. We are also studying the EM compatibility of the CryoAC DM with COMSOL code simulations with particular attention to the magnetic field generated by the bias currents towards the X-IFU TES-array, which has to be kept below the ?T value. This study has set new constraints to the wiring lines, contacts and TES shapes. In this work we will show the latest advance in the design of the new detectors, showing the main results coming from various simulations.

9905-187, Session PS5

The demonstration model of the cryogenic anti-coincidence detector for ATHENA X-IFU

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The ATHENA observatory X-ray Integral Field Unit (X-IFU) is one of the two complementary focal-plane instrument for investigating "The Hot and Energetic Universe" with unprecedented spectral performance. The X-IFU sensitivity is degraded by the particles background expected at the operating orbit, which is induced by primary protons of both galactic and solar origin. In order to guarantee the X-IFU scientific goals, it is necessary to adopt a Cryogenic AntiCoincidence (CryoAC) detector placed at about 1 mm beneath the x-ray microcalorimeter array at 50 mK. The design of such a detector has required a combination of original solutions in order to fulfil the requirements: (1) fast rise-times by means of the collection of fast a-thermal primary phonons, (2) a large area/thickness aspect ratio of about 30 to 50 cm, (3) about one hundred uniformly surface distributes small superconducting transition edge sensors (TES) with highly equalized operating characteristics, (4) properly tuned operating temperatures and

dynamic range for full signal formation at the XIFU base temperature, (5) mechanical compatibility for flight transfer to the orbit, (6) EM and thermal compatibility with the TES microcalorimeter array.

In the first phase of the design we have successfully demonstrated with several prototypes the first four issues and simulated the last two ones.

We have started the second phase in which all these detector characteristics will be combined in the so-called CryoAC Demonstration Model. It is a single silicon monolithic micro-bridged pixel with an active area of about 1 cm2. The full set of thermal, mechanical and EM requirements have been included in a new design. We have performed several fabrication tests of this peculiar detector that has been fabricated with micro-machining techniques from a single wafer of silicon. The mechanical structure design is supported by simulations, including the random displacement vibrations. The EM compatibility has needed the development of TES sensor anti-inductive biasing lines. The TES operating temperature has been obtained with the technique of the gold proximization of iridium superconducting film through a proper parameter setting of the UHV film growth facility. The detector silicon microbridges are thermally qualified after each fabrication run with low temperature tests.

We report here the overview of this work of design, simulation and parameter's qualification of the silicon monolithic micro-bridges detector and a preliminary delivery test with 60 keV gamma ray.

9905-188, Session PS5

X-Ray absorption spectroscopy on test thermal filters for the ATHENA X-IFU detector

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ATHENA is a large astrophysical observatory approved by the European Space Agency to address the science theme "Hot and Energetic Universe" (L2 mission with launch scheduled in 2028). One of the two instruments of ATHENA is the X-ray Integral Field Unit (X-IFU), an array of Transition Edge Sensor (TES) micro-calorimeters with spectral, imaging, and timing capabilities in the energy range 0.2÷12 keV.

The X-IFU will be cooled by a quite complex multi-stage liquid free cryostat down to nearly 50 mK. In order to allow the focused X-ray beam to reach the detector, a clear path is opened in the cryostat thermal and mechanical shields. Thin windows, transparent to X-rays, will be mounted on such openings to minimize IR radiation heat-load onto the cold detector array, and to keep the photon shot noise well below the intrinsic energy resolution of the TES micro-calorimeters (?EFWHM < 2.5 eV @ 6 keV).

In the current investigated design, five thermal filters will be mounted on the cryostat shields, each one consisting of a thin membrane of polyimide (approx. 50 nm) coated with aluminum (approx. 30 nm). The larger diameter filters being supported by a metal mesh with large open area. Despite the small thickness and the use of low Z materials, the thermal filters become quite opaque at E < 1.0 keV, and they essentially define the low energy response of the X-IFU.

Since the main characteristic of the X-IFU is the high energy resolution, a detailed calibration program of the thermal filters will need to be performed with high resolution X-ray spectroscopy to properly characterize the low energy instrument response. The thermal filters operate at different temperatures ranging from 300 K down to nearly 50 mK. For this reason, it is relevant to study what is the role of temperature, in the range 0.05-300 K, on the mechanical/optical performance of the filters (e.g. effects on the near edge absorption fine structures of the atomic elements in the filter material), to determine whether the calibration program needs to be performed at different operating temperatures.

We report the results of an X-ray Absorption Spectroscopy (XAS) measurement campaign on test filters of polyimide and aluminum performed in the energy range 175-1650 eV at the BACH beam-line of the Italian synchrotron ELETTRA. In this first campaign we have been able to explore the temperature range 130-300 K.

9905-189, Session PS5

The ATHENA X-IFU filter wheel

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The X-ray Integral Field Unit (X-IFU) instrument on-board ATHENA will be equipped with a filter wheel (FW) in order to optimize the outcomes of scientific observations.

The entire FW assembly comprises the positioning mechanism, the control electronics box and the wheel which will house a calibration source, closed and open positions, as well as filters. The latter are not fully defined yet, however, it is expected that, together with the thermal filters mounted on the cryostat shields, the X-IFU FW filters should provide: (i) protection against contamination, (ii) reduction of optical load from bright stars and other celestial sources in the field, and (iii) attenuation of the X-ray count rates for bright sources to avoid degradation of the instrument energy resolution.

In this contribution we present the status of the filter wheel mechanism and electronic design, as well as the current development plan for the filters.

9905-190, Session PS5

Conceptual design of the X-IFU instrument control unit on board the ESA ATHENA mission

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Athena is the L-class mission selected in the ESA Cosmic Vision 2015-2025 programme for the science theme of the Hot and Energetic Universe.

The Athena model payload includes the X-ray Integral Field Unit (X-IFU), an advanced actively-shielded X-ray microcalorimeter spectrometer for high-spectral resolution imaging, utilizing cooled Transition Edge Sensors.

This paper describes the preliminary architecture of Instrument Control Unit (ICU), which is aimed at operating all X-IFU's subsystems, as well as at implementing the main functional interfaces of the instrument with the S/C control unit.

The ICU functions include the TC/TM management with S/C, science data formatting and transmission to S/C Mass Memory, housekeeping data handling, time distribution for synchronous operations and the management of the X-IFU components (i.e. CryoCoolers, Filter Wheel, Detector Readout Electronics Event Processor, Power Distribution Unit).

ICU functions baseline implementation for the phase-A study foresees the usage of standard and space-qualified components from the heritage of past and current space missions (e.g. Gaia, Euclid), which currently encompasses Leon2/Leon3 based CPU board and SpaceWire interfaces for

the exchange commands and data between ICU and X-IFU subsystems.

Alternative architecture, arranged around a powerful PowerPC-based CPU, is also briefly presented, in the aim at endowing the system with enhanced hardware resources and processing power capability, for the handling of control and science data processing tasks not defined yet at this stage of the mission study.

9905-191, Session PS5

Updates on the background estimates for the X-IFU instrument onboard of the ATHENA mission

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ATHENA is the second large mission in ESA Cosmic Vision 2015-2025, with a launch foreseen in 2028 towards the L2 orbit. The mission addresses the science theme "The Hot and Energetic Universe", by coupling a high-performance X-ray Telescope with two complementary focal-plane instruments. One of these, the X-ray Integral Field Unit (X-IFU) is a TES based kilo-pixel array, providing spatially resolved high-resolution spectroscopy (2.5 eV at 6 keV) over a 5 arcmin FoV.

The background for this kind of detectors accounts for several components: the diffuse Cosmic X-ray Background, the low energy particles (<~100 keV) focalized by the mirrors and reaching the detector from inside the field of view, and the high energy particles (> ~100 MeV) crossing the spacecraft and reaching the focal plane from every direction. In particular, these high energy particles lose energy in the materials they cross, creating secondaries along their path that can induce an additional background component.

Each one of these components is under study of a team dedicated to the background issues regarding the X-IFU, with the aim to reduce their impact on the instrumental performances. This task is particularly challenging, given the lack of data on the background of X-ray detectors in L2, the uncertainties on the particle environment to be expected in such orbit, and the reliability of the models used in the Monte Carlo background computations. As a consequence, the activities addressed by the group range from the reanalysis of the data of previous missions like XMM-Newton, to the characterization of the L2 environment by data analysis of the particle monitors onboard of satellites present in the Earth magnetotail, to the characterization of solar events and their occurrence, and to the validation of the physical models involved in the Monte Carlo simulations. All these activities will allow to develop a set of reliable simulations to predict, analyze and find effective solutions to reduce the particle background experienced by the X-IFU, ultimately satisfying the scientific requirement that enables the science of ATHENA.

While the activities are still ongoing, we present here some preliminary results already obtained by the group. The L2 environment characterization activities, and the analysis and validation of the physical processes involved in the Monte Carlo simulations are the core of an ESA activity named AREMBES (Athena Radiation Environment Models and Effects), for which the work presented here represents a starting point.

9905-192, Session PS5

TESSIM: a simulator for the ATHENA X-IFU

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We present the design of tessim, a simulator for the physics of transition edge sensors developed in the framework of the ATHENA end to end simulation effort. Designed to represent the general behavior of TES detectors and to provide input for engineering and science studies for ATHENA, tessim implements a numerical solution of the linearized equations describing these devices. The simulation includes a model for the relevant noise sources and several implementations of possible trigger algorithms. Input and output of the software are standard FITS-files which can be visualized and processed using standard X-ray astronomical tool packages. Tessim is freely available as part of the SIXTE package (http://www.sternwarte.uni-erlangen.de/research/sixte/).

9905-193, Session PS5

Background studies for ATHENA: status of the activities at IAAT

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A low and reproducible background level is fundamental to guarantee succesful observations with ATHENA, and it is one of the requirements driving the design of the payload. In fact, the mass distribution at the focal plane has an impact on the sensitivity, producing secondaries that generate x-ray-like signals. Furthermore,some contamination may come from the optics, that can funnel the softer protons and ions. The optimization of the design can be pursued through simulations and laboratory tests able to reproduce the interaction of the radiation environment with mirrors, components and detectors. IAA/Tuebingen is one of the institutes that collaborate in the study for the ATHENA/WFI instrument.In this paper we present a report on the current status of the activities.

9905-194, Session PS5

Surface investigation and aluminum oxide estimation on test filters for the ATHENA X-IFU and WFI detectors

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The X-ray Integral Field Unit (X-IFU), one of the two instruments of the ATHENA mission, operates at temperature close to 50 mK. Such condition will be achieved using a sophisticated multi-stage cryostat. To allow the X-rays to reach the detector, windows are opened in the cryostat thermal and structural shields, and thin thermal filters are needed, that absorb IR radiation while being nearly transparent to X-rays. For the WFI a large area filter mounted on an external filter wheel is used to attenuate UV/VIS light to prevent optical load from bright sources as well as to protect the detector from molecular contamination.

In the current baseline design both the X-IFU thermal filters and WFI optical blocking filters are made with superposed aluminum and polyimide layers. These two materials are characterized by high transmission in X-rays, and in addition the metallic aluminum blocks the VIS/IR components mainly by reflection, while polyimide blocks the UV component by absorption. In principle, to increase the number of detectable X-ray photons, the thickness of aluminum should be the minimum value providing adequate reflectivity in the VIS/IR. However, a surface of aluminum always shows a nanometric film of native oxide that is not so efficient as metallic aluminum to block IR radiation and becomes nearly transparent to UV/VIS radiation. Generally this effect is more dramatic for thin films because the mass ratio between aluminum oxide and metallic aluminum increases.

In this work we employ X-ray Photoelectron Spectroscopy (XPS) with different incident energies measured at the BACH beamline of the Italian synchrotron ELETTRA to probe the surface (few nanometers) of two different filters consisting of 30 nm of aluminum deposited respectively on 45 nm of polyimide (sample filter investigated for the X-IFU) or 150 nm of polyimide (sample filter investigated for the WFI). We analyze XPS spectra to estimate the thickness of the native oxide that alters unfavorably the transmission of the filters, in order to determine the actual thickness of the metallic aluminum layer.

9905-195, Session PS5

Spectroscopic performance of DEPFET active pixel sensor prototypes suitable for the high count rate ATHENA WFI detector

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The wide field imager (WFI) planned for the advanced telescope for high energy astrophysics (Athena) provides two detectors with different functionalities. A wide field detector for the imaging of the large scale structures in the X-ray sky and a high count rate sensor for bright point sources up to the order of one Crab. The requirements for the high count rate capable detector are a throughput of >80% and a pile-up of less than 1% for a one Crab source.

The wide field detector is built of four wafer scale arrays of depleted p-channel field-effect transistors (DEPFET). In this sensor concept, the signal charges generated by an X-ray photon in the fully depleted silicon bulk are stored in an internal gate that is implemented underneath a transistor. The collected charges influence the transistor current proportional to their number. That allows the generated charge to be measured directly in the pixel without destruction.

While the DEPFET type used for the wide field detector shows worse spectral response for fast timings, the so-called Infinipix has been developed that mitigates this effect. The Infinipix concept allows the spatial separation of the collection and the readout of the charges. This is realized by using two DEPFETs per pixel. One DEPFET collects the charge while the other one is read out. In the next frame, the tasks of the two sub-pixels are interchanged. For the development of the Infinipix DEPFETs, three different layout variants were produced as 32 x 32 pixel arrays. They vary in the gate width and the design of the clear contacts which remove the collected charge during the measurement. In comparison to a standard DEPFET sensor, the current Infinipix layout implementations show several restrictions for the applicable operation voltages. This is an issue as the homogeneity over the sensor array area varies due to the fabrication technology. A small operation window sets different optimum parameters for individual transistors. This has to be optimized in future layouts. Nevertheless, the current implementations of the Infinipix arrays already show excellent spectroscopic results. The energy resolution expressed as FWHM at 6 keV is around 135 eV with a peak-to-valley of 3600 for the intended readout speed of 2.5 μs per row.

9905-196, Session PS5

The filter and calibration wheel for the ATHENA wide field imager

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One of the key instruments of ATHENA is the Wide Field Imager (WFI) which will provide imaging in the X-ray energy range of 0.2-15 keV over a field of view with the size of 40 arc min squared in combination with spectrally and time-resolved photon counting. The WFI detector, based on arrays of DEPFET active pixel sensors, is also sensitive to photons in the UV and VIS range. An appropriate blocking filter is thus needed for the large field of view detector as well as for the smaller high count rate capable detector of WFI.

The planned filter and calibration wheel will provide four positions, i.e. open aperture, optical blocking filter, closed position and calibration. The four positions can be individually aligned with the camera aperture. Since the camera has an extremely large detector with an aperture of 160x160 mm? and an additional small detector for fast measurements with an aperture of 15x15 mm?, the aforementioned features have to be doubled.

Apart from the size the design of the filter wheel comprises other challenges. Due to the large geometry mass saving is a major issue, the housing and integrated front baffle shall however also serve as proton shield. Launch environment becomes critical with respect to high loads in case of dynamic coupling if the frequencies cannot be moved far enough away from the eigenfrequencies of the instrument structure. FEM analysis has been performed in order to optimize the structural design.

Another major issue is the protection of the large filter during AIT as well as during launch. Due to the complexity of the camera head with its high number of cables and heat pipes, a vacuum chamber as filter wheel housing shall be avoided. It is investigated whether the Filter Wheel can be in atmosphere during launch with localized protection of the filters, mainly with respect to acoustic load. Results of acoustic simulation analysis are presented in order to demonstrate that the filter will withstand environmental loads.

To reduce complexity and mass, simple but reliable solutions are envisaged including the mechanical configuration as well as the motor drive and position control. This paper will describe the various challenges and provide trade-offs that have been performed. The baseline concept that fulfils the design requirements is presented and selected solutions are describe in detail.

9905-197, Session PS6

Ex luna scientia: lunar occultation as a paradigm for nuclear astrophysics

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Next-generation nuclear astrophysics investigations must address a demanding set of requirements to probe the matter and energy life-cycle in our Galaxy and throughout the Cosmos. Enhanced flux sensitivity and (near) all-sky monitoring are just two of these requirements; cost effectiveness and other programmatic restrictions pose additional challenges. These competing goals can be addressed with a paradigm change, i.e. performing investigations from lunar orbit and utilizing a new detection and imaging technique.

The Moon is a unique location for experimental astrophysics that can be leveraged to obtain novel capabilities not easily achievable in near-Earth orbit. It's unique beneficial characteristics include the dense lunar regolith, lack of an appreciable lunar atmosphere and magnetosphere, and a well-characterized background environment. Although several electromagnetic regimes can utilize these features, high-sensitivity investigations in the range 0.1-10 MeV are uniquely enabled there. Use of the Moon as a scientific platform for nuclear observations also represents an opportunity for synergistic investigations spanning topical areas in astrophysics, solar physics, and planetary/lunar science.

We will report on our development of the Moon as a platform for nuclear astrophysics utilizing the Lunar Occultation Technique (LOT). Here source fluxes are temporally modulated as they are repeatedly occulted by the Moon; the modulation, as observed by a suitably configured instrument in lunar orbit, enables the detection, imaging, and characterization of both point- and extended-sources, narrow-line and broadband sources. Key benefits include maximizing the ratio of sensitive-to-total deployed mass and the operational simplicity relative to other detection schemes. A mission based on the LOT, the Lunar Occultation Explorer (LOX), will be the first to employ occultation as the principle method to characterize the intensity, variability, and spectra of detected sources.

We will present details of the LOT and discuss the dedicated time-series analysis and statistical techniques being developed and employed. An outline of the mission concept, including primary science goals and drivers, preliminary mission sensitivity estimates, and implementation trades will also be presented. Finally, we will also report on concept validation efforts, including source detection, using in-situ measurements made from lunar orbit.

Our development program is focused on realizing the first high-energy astrophysical investigations using the Moon as a scientific platform in an effort to provide unique, achievable, and cost-effective next-generation capabilities in nuclear astrophysics.

9905-198, Session PS6

GAMCOTE: a prototype for an advanced Compton telescope

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The answers to many key questions regarding the most violent cosmic phenomena and their implications on the general evolution of the Universe are to be found in the 0.1 - 100 MeV photon energy domain. Indeed this energy window is unique for studying matter evolution, antimatter generation and very energetic phenomena in compact stars and massive black holes.

The INTEGRAL satellite from the European Space Agency (ESA) is currently observing the sky in the 15 keV to 10 MeV band. However this mission may only last a few more years which calls for the development of the next generation gamma-ray telescopes. Progresses are slow and no experiment achieved a survey sensitivity better than the COMPTEL instrument of the CGRO mission. This situation arises from the difficulties inherent to this energy domain, where the probability of photon interaction with matter reaches a minimum while the instrumental background induced by cosmic-ray particles is very high.

One of the most promising concepts for the next generation of gamma-ray space instrument is a Compton and pair-creation telescope made of two main parts: a silicon tracker optimized for Compton scattering of cosmic gamma rays and a calorimeter that absorbs the scattered photons. Such a design also shows excellent performance for higher cosmic gamma-rays energy where the pair creation regime prevails. The ASTROGAM instrument, relying on such a design, has been proposed in response of ESA's call for a fourth Medium-size mission (M4) in the "Cosmic Vision 2010-2025" program framework. An extended mission featuring a larger scale instrument and spacecraft is currently being design for the M5 Call.

In this contribution we will present the first results of the GAMCOTE ("GAMma-ray COmpton TElescope") setup, a prototype for an advanced Compton Telescope including thick (1.5 - 2 mm) double sided silicon stripped detectors coupled to a LaBr3:Ce cristal read by a 64 multi-anode photomultiplier tube. We have developed several test benches to study each detector individually, using customized readout electronics with a new data acquisition system. We will review the detector characterization work and then discuss the performance of the telescope prototype as a Compton imager.

9905-199, Session PS6

Experimental verification of the HERD prototype at CERN SPS

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The High Energy cosmic-Radiation Detection (HERD) facility is one of several space astronomy payloads of the cosmic light house program onboard China's Space Station, which is planned for operation starting around 2020 for about 10 years. The main scientific objectives of HERD are indirect dark matter search, precise cosmic ray spectrum and composition measurements up to the knee energy, and high energy gamma-ray monitoring and survey. HERD is composed of a 3-D cubic calorimeter (CALO) surrounded by microstrip silicon trackers (STKs) from five sides except the bottom. CALO is made of about 10^4 cubes of LYSO crystals, corresponding to about 55 radiation lengths and 3 nuclear interaction lengths, respectively.

The biggest advantage over previous missions is that HERD has an effective geometrical factor of >3 m^2sr for electrons and gamma rays and >2.5 m^2sr for protons and cosmic rays, which is more than one order of magnitude higher than others. Its energy resolution of 1% for electrons and gamma-rays beyond 100 GeV, 20% for protons from 100 GeV to 1 PeV. A novel method of reading out the LYSO signals by WLS fibers and image intensified CCDs is used, which can greatly reduce the complexity of onboard electronics.

Beam test with a HERD prototype, to verify the HERD specifications and the reading out method of WLSF+ICCD, was taken at CERN SPS in November, 2015. The prototype is composed of an array of 5*5*10 LYSO crystals, which is 1/40th of the scale of HERD CALO. Each crystal is coupled with one low range fiber, one high range fiber and one trigger fiber. The three groups of WLS fibers are read out by two ICCD systems and one PMT system, respectively. A set of 4 plastic scintillator detectors are allocated in front of the prototype to generate beam trigger signals. A particular trigger mode was selected for the ICCD systems to avoid contamination to the current frame. The silicon ladder located in between is for the charge measurement and position measurement of the beam particles. Verification tests of energy resolution, linearity response, angular resolution and particle separation power were implemented by choosing 10~250 GeV electrons, 350~400 GeV protons, 50~100 GeV positrons and A/Z=2 secondary particles from Pb ions. Calibration of the calorimeter was performed everyday with 50 GeV pions. The beam rate was limited to be no more than 500 cps to adapt to the frame rate of 300 Hz for the CCD chips.

Light spot on the CCD varies with different energy deposition in the corresponding crystal, because of involvement of multiple coupling interfaces inside the ICCDs. Overlapping with nearby light spots was considered in the energy reconstruction of individual crystals. The ratio of amplitude between low range fiber and high range fiber is about 50:1. Energy information can then be derived from the high range ICCD when saturation occurs in the low range ICCD. About 8 million events were acquired during the 10 days of test campaign. Rough energy resolution without energy calibration or correction is ~5% @ 10 GeV by using the low range ICCD data. Full data analysis of the beam test is under way.

9905-200, Session PS6

PANGU: a high resolution gamma-ray space telescope

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PANGU (the PAir-productioN Gamma-ray Unit) is a gamma-ray telescope with wide field of view optimized for spectro-imaging, timing and polarisation studies. It will map the gamma-ray sky from 10 MeV to a few GeV with unprecedented spatial resolution. This window on the Universe is unique to detect photons emitted directly by relativistic particles, via the decay of neutral pions, or the annihilation or decay light from anti-matter and the putative light dark matter candidates. A wealth of questions can be probed among the most important themes of modern physics and astrophysics.

The PANGU instrument is a pair-conversion gamma-ray telescope based on an innovative design of a silicon strip tracker. It is light, compact and accurate. It has been submitted as a candidate to the recent ESA-CAS Call for Joint Small Science Mission. In this proposal, the telescope consists of 100 layers of silicon micro-strip detector of 40 x 40 cm2 in area, stacked to height of about 90 cm, and covered by a top anticoincidence detector. It relies on multiple scattering effects for energy measurement, reaching an energy resolution between 30-50% for 10 MeV – 1 GeV. The novel tracker will allow the first polarisation measurement and provide the best angular resolution ever obtained in the soft gamma ray and GeV band. The same mission concept, with an enlarged acceptance, is now being prepared as a proposal for the upcoming ESA M5 mission.

In this contribution, the key science objectives, the payload concept and the expected performance of PANGU will be presented.

9905-201, Session PS6

Study of the point spread function of AGILE-GRID in spinning observation mode

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The AGILE gamma-ray space mission is dedicated to the observation of astrophysical sources of photons with energy E > 100 MeV. The satellite has been launched in April 2007 and it has just completed its ninth year of operations.

For the first two years of nominal lifetime AGILE has been operated in Pointing mode. On Nov. 2009, the AGILE scientific operations were reconfigured and since then the satellite is operating in a "spinning observing mode", surveying a large fraction (~ 70%) of the sky every day.

In this study we evaluate the capability of the AGILE Gamma-ray Imager Detector (GRID) to reconstruct in Spinning mode the arrival direction of an incident photon, quantified through the Point Spread Function (PSF), and we compare it with the PSF evaluated on Pointing mode data. To this purpose, we estimate the PSF on in-flight data taken in Spinning mode using the aperture photometry technique.

Our results show that both the AGILE-GRID PSF in Spinning mode and the scientific performances, such as the source location accuracy, are comparable to those in Pointing mode. These results thus confirm the similarity between the AGILE-GRID PSF and the LAT instrument one, on board the Fermi Gamma-ray Space Telescope, in the 100 MeV-1 GeV energy range, already shown in a previous analysis performed on AGILE Pointing data only.

9905-202, Session PS6

Gamma ray spectrometer for future Mars mission: design concept and simulation study

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One of the basic keys to an understanding of the formation and evolution of any planet is the knowledge of the elemental composition of its surface. Gamma spectroscopy on a Mars orbiter provides a unique opportunity to measure the elemental composition of a planet with an atmosphere thin enough to allow detection of gamma ray produced from the near surface rock and soil materials. Gamma Ray Spectrometer (GRS) flown on the 2001 Mars Odyssey Mission (Boynton et. al., 2002; 2007) provided concentration maps for the elements H, Si, Cl, K, Fe and Th for low and mid - latitudes (±52 degree) for the first time. The ~450 km spatial resolution of this instrument is too large to observe small, localized enrichment of Th and K. Hence a map of Th and K with improved spatial resolution is necessary over the entire Martial surface, especially more focused over some target areas, to understand whether a global magma ocean did exist on Mars or not.

We are developing Gamma Ray Spectrometer using HPGe (High Purity Germanium) detector for future Mars orbiter mission. The scientific objective is to map naturally occurring radioactive elements (Th, U, K) and other major elements (Fe, Mg, Cl, Al, Si, S, Mg). We plan to map the entire Martian surface with a spatial resolution of better than 250 km. HPGe detector requires a cooling to ~77 K temperature for reducing the detector background. The development of cooling mechanism of detector using Stirling type cryo - cooler has been initiated. This cryo - cooler is very compact in size and has high cooling efficiency. This instrument will also have Anti - Coincidence Shield (ACS) for background subtraction. Here ACS will be operated into both coincidence as well as anti coincidence mode.

GEANT4 simulation study has been carried out for the selection of ACS detector. In this simulation various Scintillator detectors (LaBr3:Ce, CeBr3, CsI, NaI, and BGO) with various thicknesses are used for ACS material. This simulation has also been repeated using HPGe as another option of ACS material. Performances of various options of ACS materials are compared based on the absorption efficiency, peak to Compton ratio, shielding effectiveness, overall geometry complexity and weight of the detector assembly. Effect of Martial atmosphere on the transmission of gamma rays has also been studied which reports the dependence of atmospheric attenuation factor on the energy of gamma rays. The transmission efficiency of Martial atmosphere for 1 MeV gamma energy comes out to be ~25%. This simulation also gives an idea of low energy cutoff of X - rays / Gamma ray which can be transmitted from the Martian surface to the Orbiter.

We will present the design concept of the instrument and preliminary results from the HPGe detector using in - house developed electronics. We will also present the comparative study of the GEANT4 simulations, carried out for various cases.

9905-203, Session PS6

Off-axis response of an x-/gamma-ray telescope based on Laue lenses

Enrico Virgilli, Univ. degli Studi di Ferrara (Italy); Ezio Caroli, Natalia Auricchio, John B. Stephen, INAF - IASF Bologna (Italy); Filippo Frontera, Piero Rosati, Univ. degli Studi di Ferrara (Italy)

Soft and medium energy X-ray astronomy (below 80 keV) has already benefitted of a mature technology which has allowed focusing instruments to have been already built and successfully employed. To date, only telescopes based on Laue lenses represent an appealing technique to extend focusing capabilities to the hard X-/soft gamma-ray band up to 600 keV. In this paper we show results based on Monte Carlo simulations for a Laue lens made from an ensemble of bent crystals. We compare the on-axis Point Spread Function (PSF) with that obtained for a source placed at different off-axis angles, thereby defining a lens geometry that preserves a good PSF and sensitivity throughout the Field Of View (FOV) of the instrument with the goal of extending it to ~ 5 arc min. Furthermore, experimental tests at the LARIX facility (Ferrara – Italy) have been carried out to validate our ray tracing model of the LAUE lens for off-axis sources.

9905-204, Session PS6

A compact and modular x- and gamma-ray detector with a CsI scintillator and double-readout silicon drift detectors

Riccardo Campana, INAF - IASF Bologna (Italy)

A future compact and modular X and gamma-ray spectrometer (XGS) has been designed and a series of prototypes have been developed and tested. The experiment envisages the use of CsI scintillator bars read out at both ends by single-cell 25 mm^2 Silicon Drift Detectors. Digital algorithms are used to discriminate between events absorbed in the Silicon layer (lower energy X rays) and events absorbed in the scintillator crystal (higher energy X rays and gamma-rays). The prototype characterization is shown and the modular design for future experiments with possible astrophysical applications (e.g. for the proposed THESEUS mission) are discussed.

9905-205, Session PS6

Characterization of a LaBr3 scintillator with multi-cell silicon drift detector readout

Fabio Fuschino, Riccardo Campana, INAF - IASF Bologna (Italy)

The characterization of a scintillation gamma-ray detector, composed by a 1/2" thick, 1/2" diameter LaBr3 crystal and a 7-cell exagonal Silicon Drift Detector readout is presented, together with possible medical and astrophysical applications.

9905-206, Session PS6

The advanced scintillator Compton telescope (ASCOT) balloon project

Peter F. Bloser, Tejaswita Sharma, Jason S. Legere, Christopher M. Bancroft, Mark L. McConnell, James M. Ryan, The Univ. of New Hampshire (United States)

We describe a project to develop new medium-energy gamma-ray instrumentation by constructing and flying a balloon-borne Compton telescope using advanced scintillator materials combined with silicon photomultiplier readouts. There is a need in high-energy astronomy for a medium-energy gamma-ray mission covering the energy range from approximately 0.4 - 20 MeV to follow the success of the COMPTEL instrument on CGRO. We believe that directly building on the legacy of COMPTEL, using relatively robust, low-cost, off-the-shelf technologies, is the most promising path for such a mission. Fortunately, high-performance scintillators, such as Lanthanum Bromide (LaBr3), Cerium Bromide

(CeBr3), and p-terphenyl, and compact readout devices, such as silicon photomultipliers (SiPMs), are already commercially available and capable of meeting this need. We have conducted two balloon flights of prototype instruments to test these technologies. The first, in 2011, demonstrated that a Compton telescope consisting of an liquid organic scintillator scattering layer and a LaBr3 calorimeter effectively rejects background under balloon-flight conditions, using time-of-flight (ToF) discrimination. The second, in 2014, showed that a telescope using an organic stilbene crystal scattering element and a LaBr3 calorimeter with SiPM readouts can achieve similar ToF performance. We are now constructing a much larger balloon instrument, an Advanced Scintillator Compton Telescope (ASCOT) with SiPM readout, with the goal of imaging the Crab Nebula at MeV energies in a one-day flight. We expect a ~4-sigma detection at ~1 MeV in a single transit. We present calibration results of the first detector modules, and updated simulations of the balloon instrument sensitivity. If successful, this project will demonstrate that the energy, timing, and position resolution of this technology are sufficient to achieve an order of magnitude improvement in sensitivity in the medium-energy gamma-ray band, were it to be applied to a ~1 cubic meter instrument on a long-duration balloon or Explorer platform.

9905-207, Session PS6

A concept for a soft gamma-ray concentrator using thin-film multilayer structures

Peter F. Bloser, Farzane Shirazi, Olof Echt, James Krzanowski, Jason S. Legere, Mark L. McConnell, John G. Tsavalas, Emily N. Wong, Paul H. Aliotta, The Univ. of New Hampshire (United States)

We are investigating the use of thin-film, multilayer structures to form optics capable of concentrating soft gamma rays with energies greater than 100 keV, beyond the reach of current grazing-incidence hard X-ray mirrors. Alternating layers of low- and high-density materials (e.g., polymers and metals) will channel soft gamma-ray photons via total external reflection. A suitable arrangement of curved structures will then concentrate the incident radiation to a point. Gamma-ray optics made in this way offer the potential for soft gamma-ray telescopes with focal lengths of less than 10 m, removing the need for formation flying spacecraft and opening the field up to balloon-borne instruments. Following initial investigations at Los Alamos National Laboratory, we have constructed and tested a prototype structure using spin coating combined with magnetron sputtering. We are now investigating whether it is possible to grow such flexible multi-layer structures with the required thicknesses and smoothness more quickly by using magnetron sputter and pulsed laser deposition techniques. We will present the results of our fabrication and gamma-ray channeling tests, and describe our modeling of the sensitivity of potential concentrator-based telescope designs. If successful, this technology offers the potential for transformational increases in sensitivity while dramatically improving the system-level performance of future high-energy astronomy missions through reduced mass and complexity.

9905-209, Session PS6

A new assembling technology of Laue lenses

Filippo Frontera, Enrico Virgilli, Piero Rosati, Univ. degli Studi di Ferrara (Italy); Ezio Caroli, Natalia Auricchio, John B. Stephen, INAF - IASF Bologna (Italy)

We will report on a new technology we have developed in our laboratory for assembling a Laue lens under development. The lens is made of bent crystals of Gallium Arsenide (GaAs, 220) with a focal length of 20 m for space applications. Thanks to the bent crystal the Pont Spread Function (PSF) of the lens is very thin with an angular spread at Full Width at Half Maximum (FWHM) of about 20 arcsecs for paraxial photons. In order to achieve this PSF it is crucial to fix the crystals to the lens frame in such way that the resin polimerization does not influence the initial position of the crystals. In this talk we will compare the gluing technologies adopted and presented in the past SPIE 2015 conference with a new technology that is very promising for achieving our final assembling goal.

9905-210, Session PS6

Simulation studies for compare: a discovery mission for MeV gamma-ray astronomy

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ComPair is gamma-ray telescope designed to detect photons in the challenging energy range from 0.2 keV to >100 MeV, where the interaction cross section is minimized and the dominant mechanism transitions from Compton scattering to pair production near 10 MeV. To measure both interactions the instrument includes a double-sided Si-strip tracker and two calorimetric layers, CZT and CsI(Tl), housed within plastic scintillator to provide rejection of charged particle events. ComPair is a wide-field instrument optimized to enhance continuum sensitivity by more than an order of magnitude and to reduce angular resolution over previous instruments in this energy range. Simulation studies of the instrument perform two primary roles, evaluating the instrument performance and exploring detailed studies of the subsystems. The spatial and energy resolution of the tracking and calorimeter elements are critical elements of the overall performance. Here we will present details of the simulated performance of the full instrument as well supporting studies of the subsystems, in particular the CZT calorimeter, for use in developing a prototype.

9905-212, Session PS6

The two-dimensional gas micro-well detectors for the advanced energetic pair telescope

Andrei Hanu, Stanley D. Hunter, Mary J. Li, Lance H. Oh, NASA Goddard Space Flight Ctr. (United States)

The Advanced Energetic Pair Telescope (AdEPT) is a 5 to 200 MeV gamma ray polarimetry mission that employs a low-density gaseous time projection chamber to achieve high polarization sensitivity and angular resolution that approaches the equivalent of the optical diffraction limit for gamma rays. To achieve this performance, AdEPT is instrumented by a large array (2 m x 2 m) of pixelized gas micro-well detectors that readout the electron-positron tracks produced when gamma rays convert in the gaseous volume. The micro-well detectors, under development at the Goddard Space Flight Center, consist of individual micro-patterned gas proportional counters than simultaneously amplify and readout the primary ionization charge falling into each well. To readout the charged, the wells are connected to X and Y electrodes on the top and bottom of the device providing two-dimensional imaging with 400 ?m position resolution. By taking advantage of silicon processing techniques, we have eliminated all outgassing of inorganic compounds and minimized the area lost due to interconnects, thus making the devices valuable for a variety of space-flight applications where large area X-ray, gamma-ray, or particle track imaging is required. In this work, we will present the initial detector design and preliminary results of the leakage current, breakdown voltage, gas gain, and energy resolution.

9905-213, Session PS6

In-depth calibration of a Laue lens prototype built at Univ. of California, Berkeley

Nicolas M. Barrière, cosine B.V. (Netherlands); Colin Wade, Univ. College Dublin (Ireland); John A. Tomsick, Space Sciences Lab. (United States); Lorraine Hanlon, Univ. College Dublin (Ireland); Steven E. Boggs, Space Sciences Lab. (United States); Peter von Ballmoos, Institut de Recherche en Astrophysique et Planétologie (France)

A Laue lens uses Bragg diffraction in the volume of a large number of small, nearly cubic crystals to concentrate soft gamma rays into a focal point. A technological demonstrator made of 48 crystals of 5 x 5 mm cross-section (12 pure Al crystals and 36 pure Fe crystals arranged into 8 partial concentric rings) was built in 2014 at UC Berkeley. This lens, designed to refocus the beam of an X-ray producing machine in the 95 - 130 keV band with a focal length of 1.5 m, was calibrated in December 2015 using a modified version of the beamline that was used to orient and glue the crystals. Here, we present the calibration method, and the results that were obtained. Finally, we take a step back and comment on the assembly process that was adopted for this prototype Laue lens, and how it could be scaled up for a full-size lens.

9905-214, Session PS6

In-depth calibration of a Laue lens prototype composed of Fe and Al mosaic crystals

Colin Wade, Univ. College Dublin (Ireland); Nicolas M. Barrière, cosine B.V. (Netherlands); John A. Tomsick, Space Sciences Lab. (United States); Lorraine Hanlon, Univ. College Dublin (Ireland); Steven E. Boggs, Space Sciences Lab. (United States); Peter Von Ballmoos, Institut de Recherche en Astrophysique et Planétologie (France)

The Laue lens uses Bragg diffraction to focus soft gamma-rays. In late 2014, the Laue lens assembly station (LLAS) at UC Berkeley was used to construct a prototype lens segment, consisting of 48 5x5 mm2 crystals - 36 Iron and 12 Aluminium. The segment is composed of 8 partial rings, each of which is aligned to diffract an energy between 90 and 130 keV. In December 2015 the prototype was tested and calibrated using a modified version of the LLAS.

The crystal mounting speed was found to be a large improvement over previous set-ups. The glue used had a 2 minute curing time instead of 5 hours as was used previously. Unfortunately the shrinkage of the glue caused significant deviations of the crystal orientation upon curing. Preliminary reflectivity measurements suggest a diffraction efficiency of between 10-20% for the lens segment.

9905-244, Session PS8

Multilayer coating of XTP telescope mirrors

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We present the coating of depth-graded W/Si multilayers on the thermally slumped glass substrates for telescopes in X-ray timing and polarization mission. The coating consists of several hundred bilayers in an optimized graded power law design with stringent requirements on uniformity and interfacial roughness. We introduce the details of the planar magnetron sputtering facility including the optimization of Ar pressure and collimating geometry which allows us to make the several thousand mirror segments required for each telescope. Results are presented on the uniformity, interfacial roughness, stress, reflectivity and scatter at hard X-ray energies.

9905-245, Session PS8

X-ray mirror module analytical design from field of view requirement and stray light tolerances

Daniele Spiga, INAF - Osservatorio Astronomico di Brera (Italy)

The design of an X-ray mirror module is a critical issue. In general, the design depends on requirements such as the effective area on-axis, the angular resolution, and the field of view, meant as the angular diameter at which the effective area is half the on-axis one. The design has also to come to terms with constraints such as the maximum mass and size allocated in the spacecraft, and the mirror module design consists in fulfilling all these requirements by populating the module with decreasing diameters until the total effective area on-axis is reached without exceeding the mass limit. However, the separation between consecutive shells has to be properly chosen, to avoid an excessive obstruction off-axis that would limit the field of view. We already know, in fact, that it is possible to determine analytically a diameter population that is obstruction-free within the field of view. Even though this solution enhances the off-axis effective area, it is always optimal because it also leaves too much spacing for stray light. The optimal choice for the spacing should hence be the necessary and sufficient one to allow the required vignetting function; but, while the computation of the total vignetting from the spacing of mirrors in the module can be done by ray-tracing, the inverse problem is difficult because it should be approached by subsequent attempts. Fortunately, the geometric vignetting of a mirror shell can be analytically determined as a function of the off-axis angle and the obstruction parameter, and the expression can be solved for the mirror shell spacing in order to set the field of view at the desired value. In this paper we show how this can be done.

9905-246, Session PS8

Four-times reflection x-ray optics and its application to x-ray telescope

Yuzuru Tawara, Ikuyuki Mitsuishi, Yasunori Babazaki, Nagoya Univ. (Japan)

Effective area of the telescope for X-ray energy $E < 10$ keV including iron K emission lines has been so far limited to less than 1000 cm2 for assumed several meter focal length X-ray telescope. To increase this effective area, we propose four-reflection telescope (FXT) with the same focal length system. To prove this possibility, we performed ray tracing simulation for FXT and found that such system can have several times larger effective area than that of 2-reflection optics. As an example, the effective area of FXT with 6 m focal length can be 3100 cm2 at 6 keV. In this paper, we will discuss other telescope performances such as angular resolution, field of view, mechanical properties and application to fine spectroscopic mission using X-ray micro-calorimeter.

9905-247, Session PS8

Development of lightweight replicated Wolter x-ray optics

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NASA'S future X-ray astronomy missions will require X-ray optics that have large effective area while remaining lightweight, and cost effective. Some X-ray missions, such as XMM-Newton , and the upcoming Spectrum-Röntgen-Gamma mission use an electroformed nickel replication (ENR) process to fabricate the nested grazing incidence X-ray telescope mirror shells for an array of moderate resolution, moderate effective area telescopes. We are developing a process to fabricate metal-ceramic replicated optics which will be lighter weight than current nickel replicated technology. Our technology development takes full advantage of the replication technique by fabricating large diameter mirrors with thin cross sections allowing maximum nesting and increase in collecting area. This will lead to future cost effective missions with large effective area and lightweight optics with good angular resolution.

Recent results on fabrication and testing of these optics is presented.

9905-248, Session PS8

Assemblies of segmented mirrors with interfacing ribs for high angular resolution x-ray telescopes: cold and hot slumped glass optics at work

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The Slumped Glass Optics technology, developed at INAF/OAB since a few years, is a competitive solution for the realization of the future X-ray telescopes with a very large collecting area, as e.g. Athena, (with more than 2 m2 effective area at 1 keV and with and an angular resolution of just 5'' HEW) or the NGHXT hard X-ray missions (with just 20 arcsec HEW at 30 keV) under study in Japan. The developed technique is based on modular elements, named X-ray Optical Units (XOUs), made of several layers of thin foils of glass, previously formed by direct hot slumping in cylindrical geometry, and then stacked in a Wolter-I configuration, through interfacing ribs. The assembly method has been refined and improved and now the approach represent a valid back-up solution to the SPO assumed as a baseline for ATHENA. Moreover, last advancements in the production of thin glass substrates may allow a great simplification of this process, avoiding the pre-forming step via hot slumping. In fact, the thickness, the strength and the flexibility of these flat glass foils (with thickness lower than 0.030 mm) allow their bending up to very small radius of curvature without breaks. In this paper we provide an update of the project development, reporting on the last results achieved. In particular, we will present the results obtained on several integrated prototypes integrated with different techniques starting from flat or pre-shaped foils.

9905-249, Session PS8

Development of low-stress Iridium coatings for astronomical x-ray mirrors

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Previously used mirror technologies are not able to fulfill the challenging needs of future X-ray telescopes. Therefore the required high precision mirror manufacturing triggers new technical developments around the world. Some aspects of X-ray mirrors production are studied within the interdisciplinary project INTRAAST, a German acronym for "industry transfer of astronomical mirror technologies". The project is embedded in a cooperation of the Aschaffenburg University of Applied Sciences and the Max-Planck-Institute for Extraterrestrial Physics (MPE). One important task is the development of low-stress Iridium coatings for X-ray mirrors based on thin glass substrates. The surface figure of the glass substrates is measured before and after the coating process by optical methods and with a profilometer. By using Stoney´s formula the coating stress can be calculated from the surface curvature difference and related to the parameters of coating deposition, allowing for the optimization of the process. The sputtering parameters might have influence also on the coating density and on the micro-roughness of the mirrors, which will be monitored during the whole activity. The technical approach for the low-stress Iridium coating development, the experimental equipment, and the obtained results will be presented within this contribution.

9905-250, Session PS8

Monte Carlo simulations of soft proton flares: testing the physics with XMM-Newton

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Low energy protons (< 100-200 keV) in the Van Allen belt and the outer regions can enter the field of view of X-ray focusing telescopes, interact with the Wolter-I optics, and reach the focal plane. The scattering of electrons by X-ray optics was expected before the launch of the Swift (NASA), Chandra (NASA), and XMM-Newton (ESA) X-ray telescopes. For this reason, a magnetic diverter for electrons, deflecting their path to the focal plane, is on board the three satellites. The funneling of soft protons was discovered after the damaging of the Chandra/ACIS Front-Illuminated CCDs in September 1999 after the first passages through the radiation belt. The use of special filters protects the XMM-Newton focal plane below an altitude of 70000 km, but above this limit the effect of soft protons is still present in the form of sudden flares in the count rate of the EPIC instruments that can last from hundreds of seconds to hours and can hardly be disentangled from X-ray photons, causing the loss of large amounts of observing time.

The accurate characterization of (i) the distribution of the soft proton population, (ii) the physics interaction coming into play, (iii) the effect on the focal plane are mandatory to evaluate the background and design the proton magnetic diverter on board the future X-ray focusing telescopes (e.g. Athena).

Several solutions have been proposed so far for the primary population and the physics interaction, however the difficulty in reaching low energy protons and precise angle measurements in laboratory makes the smoking gun still unclear.

Since the only real data available is the XMM-Newton spectrum of soft proton flares in orbit, we try to characterize the input proton population and the physics interaction by simulating, using the BoGEMMS framework, the proton interaction with a simplified model of the X-ray mirror module and the focal plane, and comparing the result with a real observation.

The analysis of ten orbits of observations of the EPIC/pn instrument show that the occurrence of flares in regions far outside the radiation belt largely

increases during summer, confirming the solar origin of the soft proton population. The Equator-S and ACE proton spectra detected respectively at a 70000 km altitude and at L1 are used for the proton population entering the optics and the combined multiple and Firsov scattering is used as physics interaction.

If the thick filter is used, the soft protons in the 30-70 keV energy range are the main contributors to the simulated spectrum below 10 keV. We are able to reproduce the proton vignetting observed in real data-sets, with a ? 50% decrease from the inner to the outer region, but a maximum flux of 0.01 counts cm^2 s-1 keV-1 is obtained resulting to be about 5 times lower than the EPIC/MOS detection and 100 times lower than the EPIC/pn one. Given the high variability of the flare intensity, we conclude that an average spectrum, based on the analysis of a full season of soft proton events is required to compare Monte Carlo simulations with real events.

9905-251, Session PS8

Distortion-free coating of mirror segments for high-resolution lightweight x-ray optics

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Stress-induced coating distortion poses a technical challenge for high resolution, large area, lightweight x-ray mirrors for space-based missions. High-density material such as iridium, deposited at room temperature, typically has high intrinsic stress of the order of several GPa. For telescopes requiring thin mirror segments with sub-arc-second resolution, deposition of such films can easily distort the mirrors. In this paper, we address the reduction of intrinsic stress of iridium film deposited by magnetron sputtering, by optimization of coating parameter such as the Argon pressure and by annealing. Distortion of mirror is further reduced to sub-arc-second level by the coating of a backside compensating film.

9905-252, Session PS8

Indirect slumping of D263 glass on fused silica mould

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The Slumped Glass Optic (SGO) group of the Max Planck Institute for Extraterrestrial physics (MPE) is analyzing and progressing the indirect slumping technology for its application to X-ray telescope manufacturing. Several aspects of the technology have been studied in the past. This year we will concentrate our activities on the slumping of Schott D263 glass on a precise machined Fused Silica mould: The concave mould was produced by the Italian company Media Lario technologies with the parabola and hyperbola side of the typical Wolter I design in one single piece. Its shape quality was estimated by optical metrology to be 6 arcsec Half Energy Width (HEW) in double reflection. The application of an anti-sticking layer is under study to avoid the adhesion of the glass on the mould during the forming process at high temperatures. The mould will be used for the slumping of mirror segments of 200 mm by 100 mm, which will be integrated in optical modules using the Alignment Integration Machine (AIV) developed at MPE. The modules will be tested in X-ray in PANTER and will be employed for vibration tests. The results of these activities will be presented in the paper.

9905-253, Session PS8

Alignment of off-plane x-ray reflection gratings using optical light

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The next generation of high resolution soft X-ray spectrometers will require large effective area and high resolving capability. One method of achieving this level of performance is through the use of off-plane reflection gratings. As X-rays will only reflect if they are incident onto a surface at a shallow graze angle, arrays of off-plane gratings have to be placed in the converging beam, generated by an X-ray optic, to achieve the necessary effective areas. To maintain the high resolving power of a single grating across this array and the increase in effective area due to the use of an array of gratings, the gratings have to be very precisely aligned to one another and fanned so that they match the convergence of the X-ray optic. This alignment is to ensure that the dispersed photons from each element arrive in the same line-spread function on the focal plane. The majority of our alignment tolerances are driven by the effective area requirement. To increase the technology readiness level of the gratings, they are scheduled to be flown on the OGRE suborbital rocket payload

Work has been completed at the University of Iowa to manufacture off-plane gratings and to develop a grating alignment test setup that allows for the alignment of the X-ray gratings using optical photons, at atmosphere, in a clean room environment. The alignment procedure forms a wavefront using a series of optics that reflects off the grating surface. This wavefront is then measured using a Shack-Hartmann sensor to observe its orientation relative to the sensor normal. A hexapod is then used to move the grating, and therefore allowing the grating surface to be aligned in pitch and roll. Yaw is aligned using high order diffraction of a laser from an optical grating that is imprinted in the corner of each grating element. The hexapod can be used to change the location of these dispersed orders, allowing the orientation of each grating in yaw to be constrained. The x, y and z positions for each grating are constrained through the mechanical tolerance of the alignment mount. The aligned gratings are mounted into an Invar module and a theodolite is used to measure the relative position of the module to the known position of the grating. This relative measurement is used to align gratings to an initial reference grating to reduce error stack-up.

This method for grating alignment has been used to produce a test array of 3 co-aligned gratings mounted into an invar module. This module has been tested at the Marshall Space Flight Center using the Stray-Light facility to confirm that the gratings in the module have been correctly co-aligned to each other.

This paper discusses the grating alignment process completed at the University of Iowa, the initial results from the X-ray testing of these aligned gratings in the Stray-Light Facility and the proposed path forward towards producing larger arrays of co-aligned gratings that will be used on the OGRE suborbital rocket payload.

9905-254, Session PS8

Analysis on the use of vacuum-oven for the indirect slumping of glass x-ray mirror segments

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The Max-Planck Institute for Extraterrestrial Physics (MPE) is involved in the investigation and optimization of the indirect slumping technique for the manufacturing of thin glass mirror segments to be assembled in lightweight X-ray telescopes. During the last year, we started to analyze the influence of vacuum environment on the results of this thermal forming process. The realization of slumping in vacuum offers in principle several advantages, like the absence of air between the glass and the mould and a cleaner environment free of contamination. Furthermore, the heat exchange is different with respect to a standard air-oven and this might have positive effects during the important cooling phase of the process. All these aspects will be considered in the paper, and the obtained results in the development of the MPE vacuum-slumping approach will be reviewed and presented.

9905-255, Session PS8

Development of an x-ray telescope using the carbon fiber reinforced plastic

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Conventional X-ray telescopes utilize the Wolter-I optics which consist of parabolic mirrors followed by hyperbolic mirrors. X-ray telescopes on board Japanese satellites such as ASTRO-H have used many thin-foil mirrors to obtain large aperture efficiency and a large effective area. However, the mirrors are conically approximated and it is difficult to keep the shape of thin mirrors good. Therefore the angular resolution of this type of telescope has been limited. We are developing an X-ray mirror using the carbon fiber reinforced plastic (CFRP) as substrate in order to improve the angular resolution; the CFRP has a high strength-to-weight ratio and can be used to realize the quadratic surface of the Wolter-I optics.

We have fabricated Wolter-I designed monolithic CFRP mirrors and made improvements in the fabrication process. The design and the fabrication method of the mirrors were based on the Hard X-ray Telescope of the ASTRO-H. The material of the mold for the CFRP substrate was renewed from Aluminum to Super-Inver, which had lower coefficient of thermal expansion than other metals. The root-mean-square errors of shape in generatrix direction of the substrates were achieved to 1~2 ?m. The reflection surface was replicated by the epoxy-replication method with the room temperature curing, which reduced the effect of print-through. In the updated CFRP mirrors, the half-power width of the reflection image by optical measurement was 0.8 arc-minutes on average. The measurement of the X-ray characterization of the updated mirrors at ISAS X-ray beam-line is scheduled December 2015.

We are also developing more intricate-structure substrate such as four-stage X-ray optics. On parallel with the mirror fabrication, we study new assembly of the mirrors from the ASTRO-H. In the assembly of the ASTRO-H telescopes, the mirrors were held by the grooves of the alignment bars, and then the positional errors of the mirrors were limited to a few ?m by the cutting accuracy of the bars.To improve positional error from the mirror assembly, we attempt to mounting on the mirrors to each others with spacer attachments.

9905-256, Session PS8

Fabrication and efficiency testing of a new generation of off-plane gratings

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Future soft X-ray spectrometers will require significant improvements in both effective area and resolving power in order to achieve their critical science goals. Off-plane gratings are one technology capable of enabling improvements in both of these spectrometer performance metrics by improving throughput into high spectral orders. Attaining this improved performance, however, requires an investment in the fabrication, development and characterization of a new generation of high performance off-plane gratings. This next generation of off-plane gratings will need to have a radially ruled groove profile matching the convergence of the X-ray telescope, a triangularly shaped facet to take advantage of the off-plane blaze effect, be optically flat so as not to aberrate the diffracted line spread function, and be fabricated over large (100 cm2) areas to increase the geometric throughput of an instrument.

Previously, off-plane gratings have been made using a holographic ruling technique followed by a directional etch to yield a blazed facet. However, this method gives little control over the groove facet angle and is incapable of realizing a high fidelity radial ruling without significant facility upgrades. Recently, a method of manufacturing off-plane gratings via a process incorporating several common microfabrication techniques has been developed. With this method, a silicon substrate is patterned via thermal nanoimprint lithography (T-NIL), an anisotropic chemical wet etch is used to create a blazed groove facet, and UV nanoimprint lithography (UV-NIL) is employed to transfer the blazed grating pattern to a flat substrate. This method has been used to yield radially ruled, blazed off-plane gratings over small (25 mm x 32 mm) formats. While this method is capable of making gratings over larger formats, patterning via T-NIL requires an imprint mold to be manufactured prior to off-plane grating fabrications. This mold is a significant investment in terms of time and cost, and must be specific to a given mission architecture at the time of manufacture.

We have begun exploring electron beam lithography (EBL) as a new means of performing the initial radial patterning of the grating grooves. The EBL-patterned substrate can then be used in the aforementioned process to yield a radially ruled, blazed off-plane reflection grating. Employing EBL as an initial patterning method offers the flexibility of producing gratings for different mission architectures and over different size formats without the upfront investment of time and cost in a grating mold required by T-NIL. Several off-plane gratings have made using this new technique have been produced, and we describe the technique in detail within.

We also report on the diffraction efficiencies of a fabricated grating tested in the Littrow configuration at the Physikalisch-Technische Bundesanstalt (PTB) soft X-ray beamline located at the BESSY II synchrotron, and compare these measured efficiencies to models of diffraction efficiency generated via PCGrate-SX software. The initial characterization of these fabricated gratings demonstrates that off-plane gratings are capable of meeting the performance requirements of future soft X-ray spectrographs.

9905-257, Session PS8

On the alignment and focusing of the Marshall grazing incidence x-ray spectrometer (MaGIXS)

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The Marshall Grazing Incidence X-ray Spectrometer (MaGIXS) is a NASA sounding rocket instrument that is designed to observe soft X-ray emissions from 0.5 - 2.0 keV energies in the solar atmosphere. The primary science goal of this experiment is to differentiate steady, low-frequency heating events from sporadic, high-frequency heating events in an active region core. For the first time, high-temperature, low-emission plasma will be observed directly with 5 arcsecond spatial resolution and 22 mÅ spectral resolution. The novel optical design consists of a Wolter - I telescope and a 3-optic grazing-incidence spectrometer. The spectrometer utilizes a finite conjugate mirror pair and a planar, varied line spaced grating that is nanoimprinted on fused-silica. The grating design is being finalized and the grating will be fabricated by the Massachusetts Institute of Technology (MIT) and Izentis LLC. Marshall Space Flight Center (MSFC) is producing the nickel replicated telescope and spectrometer mirrors using the same facilities and techniques as those developed for the ART-XC and FOXSI mirrors. The Smithsonian Astrophysical Observatory (SAO) will mount and align the flight optics based on previous experience with similar instruments, such as the Hinode X-Ray Telescope (XRT). The telescope and spectrometer assembly will be aligned in visible light through the implementation of a centroid detector assembly (CDA) -- a device designed to align the AXAF-I nested mirrors. Focusing of the telescope and spectrometer and final alignment of the system will be achieved using the X-ray beam in the Stray Light Facility (SLF) at MSFC. We present results from an alignment sensitivity analysis performed on the spectrometer, along with ZEMAX predictions for nominal return images in the CDA. We then discuss our method for aligning and focusing MaGIXS using the CDA and the SLF.

9905-258, Session PS8

Design of a medium-size x-ray mirror module based on thin glass foils

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The glass technology for X-ray mirror is under development and in the last years even better results have been achieved. Nustar is the first X-ray telescope based on slumped glass foils and its benefits are the low costs compare to the direct polishing of glass. With the slumping technique it is possible to maintain the glass mass to low values with respect to direct polishing, but in general the angular resolution is worst. Nustar mission is based on hot slumping of glass foils and its success pushed the development of activities based on slumping. A further technique based on glass is the cold shaping of foils. The improved capabilities of manufacturing thin glass foils pushed by the industrial application for screens open new possibilities for X-ray mirror. The increase in strength of thin tempered glasses, the reduction of thickness errors and the good roughness of flat foils are potentially great advantages. In this paper a design of a medium-size X-ray mirror module is analyzed, based on integration of glass stacks directly on a supporting structure that is part of the X-ray telescope and with the use of stiffening ribs as spacer between foils. The alignment of each stack is performed directly into the integration machine avoiding the necessity to a complex aligning of different modules. A typical module provides an effective area of 500 cm2 at 2 keV with a mass of about 50 kg and a focal length of 5 m.

9905-259, Session PS8

Design and performance of very hard x-ray and soft gamma-ray Wolter I telescopes

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We present conceptual designs for hard X-ray/soft gamma-ray focusing telescope using depth graded multilayer coatings.

Given the latest experimental advances in the understanding of multilayer coatings and substrate technologies, we explore the performance of focusing, reflective X-ray telescopes, based on Wolter I designs, with focal lengths varying between 20 to 50 meters and energy ranges that extend from the few keVs up to 600 keV.

We begin by briefly reviewing the compelling scientific motivation for such astrophysics mission. We then discuss how factors like uncertainty in optical constants, non-uniformities and roughness of coatings, scattering and the types of figure errors that can impact performance. After describing our design and optimization process, we present the Effective Area generated from our studies.

We also include the latest results on the development of CZT detectors capable of sub-mm position resolution in three dimensions.

9905-260, Session PS8

Simulating x-ray telescopes with McXtrace

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We take advantage of McXtrace capabilities to simulate the performance of X-ray telescopes based on Silicon Pore Optics (SPO) technologies. We use as reference the design of the optics of the planned X-ray mission Advanced Telescope for High ENergy Astrophysics (ATHENA) which is designed as a single X-ray telescope populated with stacked SPO substrates forming mirror modules to focus X-ray photons.

McXtrace is a open source monte carlo software package for simulating x-ray optics and performing virtual X-ray experiments. It was developed with the main objective of supporting optimization of X-ray beam lines and is now used in several setups such as data analysis and experiments.

McXtrace allows for modular simulations where each pore within a SPO mirror module can be traced and simulated.

9905-261, Session PS8

Ion beam figuring of glass molds for the integration of x-ray optics

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The INAF-Astronomical Observatory of Brera (INAF-OAB) is studying

the technology based on the integration of thin glass foils for making segmented high-throughput good angular resolution X-ray optics. This technology represents a back-up for the Silicon Pore Optics approach presently foreseen for the ATHENA optics, aiming at achieving an angular resolution of 5 arcsec HEW. In our labs it has developed a direct hot slumping technique for the glass foils assisted by pressure. The glass optical surface during the thermal forming process is in contact with a ceramic mould and a pressure is applied in order to force the glass to copy the mould shape. After this step, the integration of the slumped glass foils is performed by means of a purpose-built machine, able to stack the foils and create the X-ray Optical Unit, the building block of the final optical module. During this phase the foils are held in position pressed against other integration moulds made in glass, glass-ceramics or Aluminum that need to have a very precise shape since they control the final optical performances of the individual glass segments. To improve the optical figure of these moulds we foresee the use of the Ion Beam Figuring, a technology that is available internally in OAB. The institute has two facilities, one for large optics up to 1.4 meters and a second one for relatively small optics, up to 350 mm. The aim of this work is to show that we can bring the optical accuracy of the present moulds from the current 5-6 arcsec HEW (achieved after classical polishing techniques) down to 2 arcsec HEW. In this paper we describe the results obtained in the correction of the integration moulds and the steps implemented to handle the thermal load.

9905-262, Session PS8

Ion beam figuring of thin glass plates: achievements and perspectives

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Different hot slumping techniques have been developed in the last decade to shape thin glass plates in Wolter-I configuration and make them adapted for high angular resolution x-ray telescopes. The required high quality surface characteristic, both in terms of figure error and in micro-roughness, is not an easy task and the best results achieved so far are compatible with an HEW of few arcsec. In order to push forward the technology and make them adapted to high throughput x-ray optics with final HEW below 1 arcsec, a deterministic figuring technology like the ion beam figuring can be used to correct the low frequencies residual error on the glass plates.

In this paper we present the tests performed, giving a first assessment on a deterministic process definition. In particular, we report the results achieved on free standing samples of D263 and Eagle glasses, with particular care with respect to the removal function characterization, to the micro-roughness evolution and to the plate shape variation.

9905-263, Session PS8

Adjustable integration molds for x-ray optics with cold shaping: requirements and conceptual design

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The cold shaping of thin substrates is a worthwhile process for the realization of x-ray optics. The technique is based on the usage of integration molds to keep the substrate in the theoretical shape while it is fixed to a structure, which will limit at the desired level the residual spring back of the plate after the release of the constrain. Since some years, this process is in use at INAF/OAB to realize Slumped Glass Optics mirror modules by means of interfacing ribs. In principle, the optical design at a given focal length of each mirror shell is different for each radius and therefore several integration molds are necessary for an assembly of plates. Depending on the optical design of the mirror module to be realized and on the desired optical performances of the system, some simplifications can be introduced in order to reduce the number of integration molds to be realized. Nevertheless the most cost-efficient solution to the problem is to realize an adjustable integration mold pair that can be shaped to the different theoretical configurations needed for the plates. This is advantageous not only in terms of number of molds and parts to be realized but also for the reduction of integration time thanks to the simplification of the process procedure. In this paper we describe the conceptual design of the system, describing its optical design, analyzing its requirements and we report on the achieved results.

9905-264, Session PS8

Design and analysis of a modular mirror assembly for segmented x-ray optics

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Lightweight and high resolution mirrors are needed for future space-based X-ray telescopes to achieve advances in high-energy astrophysics. The Next Generation X-Ray Optics (NGXO) project at NASA's Goddard Space Flight Center is developing single-crystal silicon mirror segments to achieve better than 5 arc-seconds HPD resolution. These segments must be aligned and mounted into a stiff, stable, and strong module structure. Dozens of these modules, in turn, must be aligned and mounted into a carrier structure to create a modular x-ray mirror assembly. This paper describes the requirements for a space-flight mirror assembly, a design capable of meeting these requirements, and analysis showing the requirements can be met.

The module structures are fabricated from single-crystal silicon to match the CTE and stiffness of the mirror segments. Extensive coupon testing has been performed to characterize this stiff but brittle material. Structural analysis has been performed to demonstrate the modules are sufficiently strong for expected flight loads and that deformations from thermal gradients, gravity release, and mounting are within the error budget allocations. The modules are kinematically mounted via a system of flexures to a composite carrier structure. This interface has been optimized to minimize the module distortion and maximize the clear aperture of the mirror. The composite carrier structure has also been analyzed to demonstrate it is sufficiently strong a free of deformation. A method of module alignment into the carrier structure utilize a centroid detector assembly has been developed.

A thermal system capable of preventing unacceptable distortion of the mirror assembly has been developed and optimized for maximum performance and minimum power. Hundreds of unique mirror segments were modeled so that detailed Structural Thermal Optical Performance (STOP) analysis could be performed at the module and mirror assembly level. This paper presents the STOP results and design details driving the mirror performance. A design for a 5 arc-second HPD modular mirror assembly utilizing the NGXO single-crystal silicon mirror segments has been created and analyzed to demonstrate the system requirements can be met.

9905-265, Session PS8

Recent advances in alignment and integration of slumped glass modular x-ray mirrors at MPE using simulation and deflectometry

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The alignment and intregration facility designed and comissioned at MPE to integrate modular x-ray mirrors based on slumped glass optics uses classical collimated beam methods as well as non contact CMM techniques and the deflectometry method to provide better insights into the alignment and integration process. Especially the effect of cure shrinkage of epoxy adhesives and similiar acting thermal distortion effects can be chracterized in-situ and with high fidelity.

The use of the deflectometry method to obtain slope data from the mirror segments during integration is also an important source for validation data for numerical simulations that have been carried out for the optimization of parameters such as mirror interface position, flexibility or adhesive type. Data from all three metrology sources can also be used to correlate to PANTER x-ray data. The design of the mirror modular structure has now arrived at a configuration that uses a flexural element to cope with the above mentioned shrink and TED effects simultanously and has als evolved to a level of sophistication where a first shaker test has been carried out.

Fot future developement especially an improvement of the thermal stability of bothe the alignment and integration facility but also the mirror module is important to further improve performance. In addition a further increase in the automation of the mirror alignment and integration process is a goal.

9905-266, Session PS8

X-ray scattering on random rough surfaces

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This paper presents a new method to model X-ray scattering on random rough surfaces. An actual rough surface is (incompletely) described by its Power Spectral Density (PSD). For a given PSD, model surfaces with the same roughness as the actual surface are constructed by preserving the PSD amplitudes and assigning a random phase to each spectral component. Rays representing the incident wave are reflected from the model surface and projected onto a flat plane, which is the first order approximation of the model surface, as outgoing rays and corrected for phase delays. The projected outgoing rays are then corrected for wave densities and redistributed onto an uniform grid where the model surface is constructed. The scattering is then calculated using the Fourier Transform of the resulting distribution.

This method provides the exact solutions for scattering in all directions, without small angle approximation. It is generally applicable to any wave scatterings on random rough surfaces and is not limited to small scattering angles. Examples are given for the Chandra X-ray Observatory optics. This method is also useful for the future generation X-ray astronomy missions.

9905-267, Session PS8

Optical constants of Pt and W for current and future hard x-ray telescopes

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Accurate knowledge of the optical constants (refractive index) of the constituent materials in any x-ray optical component (e.g: mirror, filter or grating) is crucial in order to achieve the most efficient instrument design and calibration. W and Pt are among the materials frequently used in x-ray optics, either as single-layer coatings or in multilayer interference coatings. For example, the HEFT and NuSTAR missions have employed W/Si and Pt/C multilayer optics in their x-ray telescopes. There are no experimental data available for W and Pt in the vicinity of the L absorption edges (10 – 14 keV), which is part of the operational energy range of the NuSTAR mission. Tabulated values for the refractive index of W and Pt in this region rely entirely on calculations based on independent-atom approximations, which often miss the near-edge fine structure which is present due to local atomic configurations. We are presenting the first experimentally-determined values for the optical constants of Pt and W thin films, around the L absorption edges, via transmission measurements at beamline 1-BM-C at the Advanced Photon Source synchrotron at Argonne National Laboratory. Additional transmission measurements at 0.05 – 1.3 keV (which includes the N and O absorption edges of W and Pt) were obtained at beamline 6.3.2. of the Advanced Light Source synchrotron at Lawrence Berkeley National Laboratory. The dispersive part of the refractive index was determined from the absorption data via a Kramers-Kronig transformation.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344. Funding was provided by NASA project 13-APRA13-0091.

9905-268, Session PS8

Development of manufacture of mirror glass substrate for x-ray timing and polarization observatory

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In China, X-ray timing and polarization (XTP) observatory will have a collection area of 9,000 cm2 at 2~6 keV. The observatory consists of five identical hard X-ray telescopes and ten identical soft X-ray telescopes. The angular resolution is about 1 arcminute of HPD (half-power diameter). Each telescope consists of a large number of mirror segments precisely assembled together. Our development of the minor glass substrate is presented in this manuscript. These substrates are produced by slumping commercially available thin glass sheets. Here, we report on our work of manufacturing these substrates. The optimization of the slumping process is described and optimal procedure parameters are reported. The figure error of slumped glass substrates was measured by a laser scanner and an interferometer with CGH. The measured demonstrated that the figure error is lower enough for the construction of XTP telescopes.

9905-78, Session 17

The wide-field imager instrument for ATHENA

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The WFI (Wide Field Imager) instrument is planned to be one of two complementary focal plane cameras on ESA's next X-ray observatory Athena. It combines unprecedented survey power through its large field of view of 40 arcmin x 40 arcmin together with excellent count-rate capability (≥ 1 Crab). The energy resolution of the silicon sensor is state-of-the-art in the energy band of interest from 0.2 keV to 15 keV, e.g. the full width at half maximum of a line at 6 keV will be ≤ 150 eV until the end of the nominal mission phase. This performance is accomplished by using DEPFET active pixel sensors with a pixel size of 130 μm x 130 μm well suited to the on-axis angular resolution of 5 arcsec of the mirror system. Each DEPFET pixel is a combined detector-amplifier structure with a MOSFET integrated onto a fully depleted 450 μm thick silicon bulk. Two different types of DEPFET sensors are planned for the WFI instrument: A set of four large-area sensors with in total 1024 x 1024 pixels and a single smaller gateable DEPFET sensor matrix optimized for high count-rate observations. This high count-rate capable detector shall permit for bright point source with an intensity of 1 Crab a throughput of more than 80% and a pile-up of less than 1%.

The fast readout of the DEPFET sensor matrices is facilitated by an ASIC development, called VERITAS2. Together with the Switcher-A, another ASIC that allows for readout of the DEPFET in rolling shutter mode, these elements form the key components of the WFI detectors. The detectors are surrounded by a graded-Z shield that has in particular the purpose to avoid fluorescence lines that contribute to the instrument background. Together with ultra-thin coating of the sensor and particle identification by the detector, the particle induced background shall be minimized in order to achieve the scientific requirement of a total background value smaller than 5 x 10-3 cts/cm2/s/keV.

Each detector has its dedicated electronics for supply and data acquisition. Due to the high frame rate in combination with the large pixel array, signal correction and event filtering have to be done onboard and in real time as the raw data rate would exceed the feasible telemetry rate by far.

The data streams are merged and compressed in the Instrument Control and Power distribution Unit (ICPU). The ICPU is the data, control and power interface of the WFI to the Athena satellite that is orbiting the Lagrange point L2 in a Halo orbit.

The WFI instrument comprises in addition a filter wheel in front of the camera as well as an optical stray-light baffle.

Technical budgets have been defined for the WFI instrument in the current phase A of the Athena project. Furthermore, breadboard models will be developed to demonstrate a technical readiness level of at least 5 for the various WFI subsystems before mission adoption.

9905-79, Session 17

ATHENA wide field imager key science drivers

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We will present the key science drivers for the Athena Wide Field Imager (WFI) and their translation into the critical instrument parameters. The WFI will be designed to provide excellent point source sensitivity and grasp for performing wide area searches for high-redshift AGN, Compton Thick AGN, and early galaxy groups. In-depth studies of the outskirst of nearby clusters of galaxies will similarly make use of the large field of view coupled and push the requirements on the instrumental background. High time resolution and throughput and low pile-up for bright Galactic compact objects will enable reverberation mapping and spin measurements.

9905-80, Session 17

Studies of prototype DEPFET sensors for the wide field imager of ATHENA

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The wild field imager (WFI) camera of the advanced telescope for high energy astrophysics (ATHENA) will combine an excellent spectroscopic performance and high count rate capability with a large field of view. DEPFET active pixel sensors are best suited to accomplish these demanding requirements. Each DEPFET consists of a p-channel field effect transistor, which is placed on a fully depleted, back side illuminated silicon bulk. The focal plane detector of the WFI will be composed of four large arrays to cover the large field of view of 40x40 arcmin2 and one small array that provides a high count rate capability.

Each of the four large arrays consists of 512x512 pixels with a size of 130x130 μm2. The different rows can be individually switched on and off and are consecutively sampled with a parallel multichannel readout. To achieve a full frame time resolution below 5 ms, a readout time per row below 10 μs becomes necessary.

Charge, which is generated inside the silicon bulk is collected in a potential minimum below the transistor gate. Each collected electron modulates the channel conductivity. The DEPFET pixels can be read out in two different modes. The source follower configuration reads out the voltage step on the source nodes of the pixels, while the drain readout mode acquires the drain current of the devices. The advantage of the drain readout are fixed potentials so that no settling times are needed. On the other hand, readout in source follower mode allows a larger variation in the operating parameters of the transistors that could be caused by inhomogeneities over the sensor area. Both readout modes are available on the used VERITAS-2 readout ASIC. They have been studied and compared by the use of 64x64 pixel prototype structures. Furthermore, the effect of different timings on the spectral performance was investigated in the context of WFI specifications. A key requirement is a full width at half maximum (FWHM) of not worse than 150 eV at 6 keV until the end of the mission.

9905-81, Session 17

WFI electronics and on-board data processing

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The Wide Field Imager is one of the two instrument on-board the ATHENA observatory. Its main scientific objective is to perform observations of the X-ray sky in the energy range of 0.2 keV up to 15 keV with an end-of-life spectral resolution better than 150 eV (at 6 keV) and a frame rate higher than 200 Hz. The field of view will be 40 arc min squared wherefore a focal plane array with four large sensors each with a size of 512 times 512 pixels will be developed. In this presentation the WFI on-board electronics and data processing concept will be described.

DEPFET sensors are used for the detection of X-ray photons. DEPFET pixels convert incoming photons into charges which are read-out by ASICs, called VERITAS-2. These front-end ASICs convert pixel charges into analog voltages which are digitized in the WFI Detector Electronics. One of the challenges for the electronics is to process the data in real-time. The analog data stream generated by the ASICs is in the order of 2*10^8 pixels per second distributed over 32 channels which are guided to 4 Detector Electronics units, each of which processes one quadrant of the large sensor array. In order to perform event recognition, the data stream needs

to be processed. First, offset maps have to be generated by calculating each pixel's baseline level averaged over some hundreds of dark frames. Second, noise maps are calculated that provide the fluctuations for each pixel. With the use of the generated maps, offset subtraction is performed for all pixels of the frame while the common mode is corrected row-wise. Event filtering is then performed by selection of the signals with an amplitude higher than the lower event threshold but not exceeding an upper threshold. Invalid events that are e.g. due to MIPs (minimum ionizing particles) are rejected by algorithms. This pre-processing performed by the Detector Electronics significantly reduces the data and only forwards relevant science data in form of an event list. The Instrument Control Unit finally provides algorithms for loss-less data compression of the even lit such that the maximum downstream rate of approximately 75 Gbit per day is met.

The data processing electronics hardware is distributed over several WFI subsystems: DEPFET sensors and frontend ASIS are located inside the Camera Head. Data pre-processing inside the Detector Electronics will be performed in an FPGA-based frame-processor. FPGA external memory will be used to store offset and noise maps wherefore a cache memory like architecture has to be designed. Fast real-time read and write memory access combined with robustness against radiation damage (e.g. bit-flips) has to be ensured by the frame-processor design.

Newly developed hard- and software concepts of WFI electronics derived from XMM-Newton and eROSITA heritage are presented. First results of WFI breadboard laboratory electronics will be shown. Together with the results of data processing simulations, these measurement results will consolidate the WFI electronics architecture and define the technical requirements necessary for WFI hardware development.

9905-82, Session 17

Thermal analysis of the WFI on the ATHENA observatory

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The WFI (Wide-Field Imager) instrument is one of two instruments of the ATHENA (Advanced Telescope for High-ENergy Astrophysics) mission. ATHENA is the second L-class mission in ESA's Cosmic Vision plan with launch in 2028 and will address the science theme "The Hot and Energetic Universe" by measuring hot gas in clusters and groups of galaxies as well as matter flow in black holes.

A moveable mirror assembly focusses the X-ray light to the focal plane of the WFI. The instrument consists of two separate sensors, one large DEPFET array with 512x512 pixels and one small, fast DEPFET detector with 64x64 pixels and a readout time of only 1.3ms. An angular resolution of 5" will be achieved. The rather large field of view of 40'x40' in combination with rather high power consumption is challenging not only for the thermal control system.

DEPFET sensors as well as front-end electronics and electronics boxes have to be cooled, where a completely passive cooling system with radiators and heat pipes is highly favored. In order to reduce the necessary radiator area, three separate cooling chains with three different temperature levels have been foreseen. So only the DEPFET sensors are cooled down to the lowest temperature of about 180K, while the front-end electronics is supposed to be operated between 250K and 270K. The electronics boxes can be operated at room temperature, nevertheless the excess heat has to be removed.

After first estimations of heat loads and radiator areas, a more detailed model of the camera head has been used to identify gradients between the cooling interfaces and the components to be cooled. This information is used within phase A1 of the project to further optimize the design of the instrument, e.g. material selection.

9905-83, Session 18

The ATHENA x-ray integral field unit

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The X-ray Integral Field Unit (X-IFU) on bard the Advanced Telescope for High Energy Astrophysics (Athena), ESA's second large mission of its Cosmic Vision science program, will provide spatially resolved high resolution (less than 2.5 eV up to 7 keV) spectroscopy over a field of view of 5 arc minute equivalent diameter. The X-IFU is baselined as a large format array of Transition Edge Sensors (TES) connected to a thermal bath at 50 mK. The cryogenic chain is composed of a series of mechanical coolers (Stirling, Joule Thomson, and Pulse Tube) with the last stage being a sorption Adiabatic Demagnetization Refrigerator. The readout of the TESs uses a baseband feedback loop and is based on frequency domain multiplexing, with the event reconstruction performed on-board. The X-IFU is now entering a phase A study, with the Preliminary Instrument Design due around the end of 2017. In this paper I will recall the Athena scientific objectives specific to the X-IFU and show how the derived Athena science requirements flow down into the X-IFU specifications. I will also introduce the instrument level trade-offs that are currently being performed and present a preliminary design of the instrument, as provided for the Mission Consolidation Review of the Athena mission.

The X-IFU will be provided by an international consortium led by France, The Netherlands and Italy, with ESA member state contributions from Belgium, Finland, Germany, Poland, Spain, Switzerland, with additional contributions from the United States and Japan.

9905-84, Session 18

X-IFU Instrument: technical challenges and preliminary design

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The X-ray Integral Field Unit (X-IFU) is a part of the Advanced Telescope for High Energy Astrophysics (Athena), ESA's second large mission of its Cosmic Vision science program. This instrument is developed by a large international consortium under a French leadership.

The Netherlands and Italy, with Belgium, Finland, Germany, Poland, Spain, Switzerland, are the European contributors, with the United States and Japan as international partners. The X-IFU instrument is located at the focus of a 12 meter focal length and 3 meter diameter mirror. Among its performance requirements, the spectral resolution (2.5 eV up to 7 keV) is quite challenging. The paper shall first address the technical challenges to be faced (large format array of Transition Edge Sensors cooled down to a 50 mK, the Thermal Control, EMI/EMC, micro-vivrations and read-out issues including the multiplexing process of the signal, etc.) and then shall present the preliminary design of the X-IFU instrument.

9905-85, Session 18

TES pixel parameter design of the microcalorimeter array for the x-ray integral field unit on ATHENA

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The X-ray integral field unit (X-IFU) proposed for ESA's Athena X-ray observatory will consist of ~ 4000 transition edge sensor (TES) x-ray microcalorimeters optimized for the energy range of 0.2 to 12 keV. The instrument will provide unprecedented spectral resolution of ~ 2.5 eV at energies of up to 7 keV and will accommodate photon fluxes of 1 mcrab (100 cps) for point source observations. The original baseline configuration is a uniform large pixel array (LPA) of 5" pixels that is read out using frequency domain multiplexing (FDM). However, a new configuration under study incorporates a small pixel array (SPA) of 2" pixels in the central 30"x30" portion. This hybrid array configuration would be designed to accommodate higher incident fluxes of up to 10 mcrab (1000 cps) for point source observations whilst still meeting the required energy resolution requirements. In this paper we report on the TES pixel designs that are being optimized to meet these proposed LPA and SPA requirements. In particular we describe details of how important TES parameters are chosen to meet the specific mission criteria such as energy resolution, count-rate and quantum efficiency. This includes details of key TES properties such as the small signal transition parameters, thermal design of the pixels and absorber composition. Performance trade-offs between different design options will be highlighted. The basis of the pixel parameter selection is discussed in the context of existing TES arrays that are being developed for solar and x-ray astronomy applications. These detector parameters are being used as the basis for determining the requirements for the read-out electronics, on-going studies of signal processing options for X-IFU and provide the inputs for science simulations. Although the primary readout technology for the X-IFU will utilize AC biased pixels read out with FDM, most of the pixel development to date has been focused on optimizing DC pixel performance. We describe latest results on DC biased diagnostic arrays as well as large format kilo-pixel arrays and discuss the potential differences in pixel implementation that may be required to optimize performance in an AC biased circuit.

9905-86, Session 18

The focal plane assembly for the ATHENA x-ray integral field unit instrument

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The X-ray Integral Field Unit (X-IFU) on ESA's Athena X-ray observatory will be an imaging microcalorimeter providing high spectral resolution imaging with both high count-rate capability and a large field-of-view. The X-IFU focal plane assembly (FPA) will contain the instrument's cryogenic detectors and their superconducting readout electronics, while also shielding them from their operating environment on the 2 K stage of the instrument's cryostat. This paper will describe the preliminary design concept for the focal plane assembly and identify critical technology development activities that will be required to realize this concept.

X-IFU will employ a ~ 3840-pixel TES microcalorimeter array to provide high spectral-resolution imaging over 0.2-12 keV of both bright point-sources and an extended field-of-view. This sensor array will be operated using frequency domain multiplexed SQUID readout electronics, with a two-stage SQUID amplifier chain providing low-noise readout of the TES detectors with sufficient gain to drive the cables running to the instrument's warm electronics and overcome conducted noise in this interface, while also minimizing power dissipation on the instrument's low temperature stages.

With very weak extended sources such as galaxy clusters being among the key astronomical targets to be observed by X-IFU, critical elements of the FPA design will be both active and passive elements to suppress spurious events in the detector's output signal due to the interaction of cosmic rays, or secondary particles generated by cosmic ray events, with the sensor array. This requires the use of a cryogenic anti-coincidence (Cryo-AC) detector, a second TES detector operated in close proximity to the sensor array, in order to detect cosmic rays passing through the sensor array and secondaries so that these can be flagged in off-line data processing.

The sensor array and its SQUID readout electronics are particularly sensitive to their environment, including stray-light from the thermal environment of the cryostat and spacecraft, out-of-band photons coming from sky sources, high-frequency electric fields radiated by sources such as the spacecraft's downlink antennas, conducted electrical noise in the cryo-harness between the FPA and its warm electronics, and quasi-static

magnetic fields radiated by sources such as the cryo-coolers that are used to provide the focal plane assembly's low-temperature environment. The external noise sources will be suppressed by a multi-layer shielding design to allow the required low-noise detector performance to be achieved within the expected on-ground and in-flight environment.

Finally, the focal plane assembly will be operated in a cryostat in which low-temperature cooling power is constrained by a combination of technology and spacecraft resources. As such, the assembly's thermal design is optimized to minimize the cooling power required at the lowest temperature levels, with a two-layer thermal suspension system isolating the detectors at 50 mK from the 2 K environment of the cryostat's cold stage, the design of which is further driven by strength and stiffness requirements defined to ensure survival of launch vibration loads.

9905-87, Session 18

Preliminary thermal architecture of the X-IFU instrument

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The ESA Athena mission will implement 2 instruments to study the hot and energetic universe. The X-ray Integral Field Unit (X-IFU) will provide spatially resolved high resolution spectroscopy. This high energy resolution of 2.5 eV at 7 keV could be achieved thanks to TES (Transition Edge Sensor) detectors that need to be cooled to very low temperature. To obtain the required 50 mK temperature level, a careful design of the cryostat and of the cooling chain including different technologies in cascade is needed. The preliminary cryogenic architecture of the X-IFU instrument that fulfils the TES detector thermal requirements is described. In particular, the thermal design of the detector focal plane assembly (FPA), that uses three temperature stages (from 2 K to 50 mK) to limit the thermal loads on the lowest temperature stage, is described. The baseline cooling chain is based on European and Japanese mechanical coolers (Stirling, Pulse tube and Joule Thomson coolers) that precool a sub Kelvin cooler made of a 3He sorption cooler coupled with a small ADR (Adiabatic Demagnetization Refrigerator). Preliminary thermal budgets of the X-IFU cryostat are presented and discussed regarding cooling chain performances. Various cryochain options are also discussed and some preliminary thermal sensitivity analyses are presented.

9905-88, Session 18

The cryogenic anti-coincidence detector for ATHENA X-IFU: a program overview

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The ATHENA observatory, the second large-class ESA mission in the context of the Cosmic Vision 2015-2025, is scheduled to be launched on 2028th at L2 orbit. One of the two instruments at the focal plane is the X-IFU (X-ray Integral Field Unit): it is a TES-based kilo-pixels array able to perform simultaneous high-grade energy spectroscopy (2.5 eV at 6 keV) and imaging over the 5 arcmin FoV.

The X-IFU sensitivity is degraded by the particles background, which is induced by protons of both solar and Cosmic Rays origin, and secondary electrons. The studies performed by Geant4 simulations depict a scenario where it is mandatory the use of background reduction techniques. These combine an active anticoincidence detector and a passive electron shielding to reduce the background expected in L2 orbit down to the goal level of 5E-3 cts/cm^2/s/keV, so enabling the characterization of faint or diffuse sources (e.g. WHIM or Galaxy outskirt).

From the detector point of view, this is possible by adopting a Cryogenic AntiCoincidence (CryoAC) placed within a proper optimized environment surrounding the X-IFU TES array. The CryoAC is a 4-pixels detector made of Silicon absorbers sensed by Ir:Au TESes, and placed at a distance < 1 mm below the TES-array.

On October 2015 the X-IFU Phase A program has been kicked-off. The first model (DM1, Demonstration Model 1) of the CryoAC will be made of 1 pixel "bridges-suspended" and will address the final design of the CryoAC. The delivery to the FPA development team for integration is foreseen in 2016.

Both the background studies and the detector development work are on-going to provide confident results about the expected residual background at the TES-array level, and the single pixel design to produce a detector for testing activity on 2016.

Here we will provide an overview of the CryoAC program.

We will discuss some details on the background assessment having impacts on the CryoAC design, and we will give information on both the last single pixel characterization and on the structural issues. We will conclude with some programmatic aspects.

9905-89, Session 19

The Compton spectrometer and imager

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The Compton Spectrometer and Imager (COSI) is a wide-field gamma-ray telescope (0.2-5 MeV) designed to probe the origins of Galactic positrons, uncover sites of nucleosynthesis in the Galaxy, and perform pioneering studies of gamma-ray polarization. COSI uses a compact Compton telescope design, resulting from a decade of development under NASA's APRA program. COSI performs groundbreaking science by combining improvements in sensitivity, spectral resolution, and sky coverage. We have built the COSI instrument and flight systems for ULDB flights. COSI will fly

on a NASA superpressure balloon from New Zealand in April 2016, the first science flight for NASA's ULDB program.

COSI is a wide-field survey telescope designed to perform imaging, spectroscopy, and polarization measurements. It employs a novel Compton telescope design utilizing a compact array of cross-strip germanium detectors (GeDs) to resolve individual gamma-ray interactions with high spectral and spatial resolution. The COSI array is housed in a common vacuum cryostat cooled by a mechanical cryocooler. An active CsI Shield encloses the cryostat on the sides and bottom. The FoV of the instrument covers 25% of the full sky at a given moment.

The COSI instrument builds upon considerable heritage from the previous Nuclear Compton Telescope (NCT) balloon instrument that underwent a successful technology demonstration flight in June 2005 from Fort Sumner, NM, a successful "first light" science flight from Fort Sumner in May 2009, and quickly turned around and delivered on time for a launch campaign from Alice Springs, Australia in June 2010, where it unfortunately suffered a launch mishap. The COSI instrument and Flight System are rebuilt under the NASA/APRA program as a ULDB payload. COSI underwent a short flight from Antarctica in 2014, terminated early due to technical difficulties with the balloon. COSI was recovered and is now flight ready for the April 2016 launch from New Zealand.

In this talk, we will present the COSI instrument and payload, preliminary results from the April 2016 flight, as well as the overall science goals of the COSI program.

9905-90, Session 19

MeV gamma-ray observation with a well-define point spread function based on electron tracking

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MeV gamma-ray astronomy at the energy range of 0.1-100 MeV is an unique window for observing nucleosynthesis, and it also provides the information on particle acceleration in active galactic nuclei or gamma-ray bursts, the strong gravity potential of black holes, the interaction of cosmic-ray and interstellar matter in the Galactic plane. However, the observation in this energy band is not advanced in comparison with other bands, because there is no imaging method having a sharp point spread function (PSF) and a powerful background rejection. In the observation of SN2014J by SPI/INTEGRAL, the signal of 847 keV from Co-56 was detected with the significance of 4.7 sigma, but the expected significance based on the count rate of SPI is ~100 sigma if we can suppress the instrumental background completely with a sharp point spread function (PSF).

For the next generation MeV gamma-ray telescope, we are developing an electron-tracking Compton camera (ETCC), which consists of a gaseous time projection chamber as an electron tracker and pixel scintillator arrays as an absorber. The track of Compton-recoil electron restricts the gamma-ray incident direction with powerful background rejection based on particle identification and Compton-scattering kinematic test. Because an ETCC detect the incident direction event by event, we can define a PSF of an ETCC as similar to usual telescopes. Moreover, we confirmed that the PSF of Compton camera strongly depends on the accuracy of Compton-recoil direction. For the future observation with the sensitivity of 1 mCrab, an ETCC will require the accuracy of Compton scattering angle (angular resolution measure: ARM) of ~2 degrees and the accuracy of Compton-recoil direction (scatter plane deviation: SPD) of ~5 degrees.

Now we are constructing a 30 cm-cubic ETCC for the second balloon experiment: Sub-MeV gamma ray Imaging Loaded-on-balloon Experiment: SMILE-II. The current ETCC has an effective area of ~1cm2 at 300 keV, a PSF of ~10 degrees (ARM and SPD are ~5 degrees and ~100 degrees, respectively) at FWHM for 662 keV, and a large field of view of ~3 sr. We will upgrade this ETCC to an effective area of several cm2 and a PSF of ~5 degrees using a CF4-based gas. Using the upgraded ETCC, our observation plan of SMILE-II is the mapping of electron-positron annihilation line and 1.8 MeV from Al-26. In this presentation, we will report current performance and our observation plan.

9905-91, Session 19

The e-ASTROGAM mission

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e-ASTROGAM is a gamma-ray observatory to be proposed as ESA's M5 Medium-size mission by a large Collaboration comprising about 250 scientists from 18 countries. It is dedicated to the observation of the Universe with unprecedented sensitivity in the energy range 0.3 – 100 MeV, extending up to GeV energies. In this energy window, a variety of phenomena and sources await their discovery and many foundational questions can be answered. e-ASTROGAM will also feature a groundbreaking capability for measuring gamma-ray polarization, thus accessing a new observable that can provide valuable information on the source geometry and the emission processes.

e-ASTROGAM will operate as an open astronomical observatory, with a core science focused on (1) the high-energy mysteries of the Galactic center and inner Galaxy, including the supermassive black hole activity, the Fermi Bubbles, the origin of the Galactic positrons, and dark matter signatures in a new energy window; (2) nucleosynthesis and propagation of heavy elements in our Galaxy and beyond, including the life cycle of elements produced by supernovae in the Milky Way and the Local Group of galaxies; (3) activity from extreme particle accelerators, including disk-jet transitions in active galactic nuclei and the origin of the extragalactic gamma-ray background. e-ASTROGAM will be ideal for the study of high-energy sources in general, including pulsars and pulsar wind nebulae, accreting neutron stars and black holes, supernova remnants, soft gamma-ray repeaters, gamma-ray bursts, and active galactic nuclei. It will also provide important contributions to solar and terrestrial physics. e-ASTROGAM will be uniquely complementary to a variety of ground and space observatories ranging from radio, optical, X-ray and TeV energies, as well as to neutrino and gravitational wave detectors.

The e-ASTROGAM payload consists of a single instrument for the simultaneous detection of Compton and pair-producing gamma-ray events. It consists of three main detectors: (1) a silicon tracker based on the technology of double sided Si strip detectors readout by an ultra low-noise front-end electronics, (2) an imaging calorimeter made of an assembly of scintillation crystals with state-of-the-art readout, and (3) an anticoincidence system designed with segmented panels of plastic scintillators covering the payload. The e-ASTROGAM instrument inherits from predecessors such as MEGA, AGILE, and Fermi, but takes full advantages of recent progresses in silicon detectors and readout microelectronics to achieve measurement of the energy and 3D position of each interaction with an excellent spectral and spatial resolution. It is further based on an innovative design, which minimizes any passive material in the detector volume. The ideal orbit for e-ASTROGAM is an equatorial low-Earth orbit of altitude in the range 550 - 600 km, with an inclination $i < 2.5°$ and eccentricity $e < 0.01$. The foreseen launcher is Ariane 6.2.

9905-92, Session 19

The development of a low energy Compton imager for GRB polarization studies

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The Gamma Ray Polarimeter Experiment (GRAPE) is designed to investigate one of the most exotic phenomena in the universe – gamma-ray bursts (GRB). There has been intense observational and theoretical research in recent years, but research in this area has been largely focused on studies of time histories, spectra, and spatial distributions. Theoretical models show that a more complete understanding of the inner structure of GRBs, including the geometry and physical processes close to the central engine, requires the exploitation of gamma-ray polarimetry. Over the past several years, we have developed the GRAPE instrument to measure the polarization of gamma-rays from GRBs over the energy range of 50 to 500 keV. GRAPE is a large FoV instrument with a sensitive energy range covering the peak energy distribution of GRBs. The design is based on an array of independent modules, each of which consists of an array of (high-Z and low-Z) scintillator elements read out by a multi-anode PMT (MAPMT). Our eventual goal is to fly GRAPE on a long duration balloon (LDB) platform to collect data on a significant sample of GRBs. Our experience with two balloon flights (in 2011 and 2014), coupled with further design efforts focused on orbital payloads, has led to an improved polarimeter concept that represents a natural evolution of the current design. The new concept employs a large number of optically-isolated scintillator elements, each of which is designed to provide a depth-of-interaction (DOI) using two (or perhaps more) readout sensors. The resulting three-dimensional location data provides a moderate level of Compton imaging capability (1 sigma angular resolution of 10-15°). Even this level of imaging can be used to significantly reduce the instrumental background by limiting the impact of the cosmic diffuse flux, dramatically improving the polarization sensitivity. Here we shall describe this concept and the expected performance for GRB polarization measurements. We will also describe our efforts to develop a working prototype, which will be initially focused on the readout technologies (including the use of SiPMs) that will provide DOI without adversely impacting the overall instrument performance.

9905-93, Session 19

Performance study of the gamma-ray bursts polarimeter POLAR

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The Gamma-Rays Bursts (GRBs) phenomenon is one of the most interesting topics in astrophysics. However, due to the limits of the current observation results, we know little about the GRB's prompt radiation mechanisms. The theorists predict that the polarization property of the GRB's prompt emissions may play a key role in distinguishing the emission mechanisms of GRB. Therefore, more and more polarimeters as well as precise GRB's prompt emission polarization measurement results are eagerly needed to unveil the mystery of radiation mechanism of GRB's central engine.

POLAR is a novel compact space-borne Compton polarimeter conceived for a precise measurement of hard X-ray/Gamma-ray polarization and optimized for the detection of the prompt emission of Gamma-Ray Bursts (GRB) in the energy range between 50 keV to 500 keV. The detector of POLAR consists of 25 detector modular units (DMU). Each DMU is composed of 64 low-Z plastic scintillator bars, read out by a flat-panel multi-anode photomultiplier H8500 and ASIC front-end electronics. The incoming photons undergo Compton scattering in the bars and produce a modulation pattern. Both simulations and hard X-ray synchrotron radiation experiment results have shown that the polarization degree and polarization angle can be retrieved from this pattern with the accuracy necessary for pinning down the GRB mechanisms.

As POLAR consists totally 1600 detection channels (in a 40?40 array), we studied the non-uniformity of their gains, low thresholds and pedestals which may affect the overall performance of POLAR in-orbit. In the same time, the gains, pedestals as well as some other performances of POLAR may also be affected by the environmental factors, like the temperature, vibration or shock experiences. All these performances have also been studied with dedicated tests or experiments.

With the efforts by the collaborators from China and Switzerland, POLAR has experienced the Demonstration Model (DM) phase, Engineering and Qualification Model (EQM) phase, Qualification Model (QM) phase, and now a full Flight Model (FM) of POLAR has been constructed. The FM of POLAR has passed the environmental acceptance tests (thermal cycling, vibration, shock and thermal vacuum tests) and experienced the calibration tests with radioactive sources and 100% polarized Gamma-Ray beam at ESRF after its construction. POLAR will be installed on-board the Chinese spacelab TG-2 in view of a flight expected in 2016.

The design of POLAR, performance study results, calibration results as well as the current status and progress of the project will be all presented in this paper.

9905-94, Session 19

First flight of the gamma-ray imager/polarimeter for solar flares (GRIPS) instrument

Nicole Duncan, Univ. of California, Berkeley (United States); Pascal Saint-Hilaire, Space Sciences Lab. (United States); Albert Y. Shih, NASA Goddard Space Flight Ctr. (United States); Gordon J. Hurford, Hazel M. Bain, Space Sciences Lab. (United States); Mark S. Amman, Lawrence Berkeley National Lab. (United States); Brent Mochizuki, Andreas Zoglauer, Steven E. Boggs, Robert Lin, Space Sciences Lab. (United States)

The Gamma-Ray Imager/Polarimeter for Solar flares (GRIPS) instrument is a balloon-borne telescope designed to study solar-flare particle

acceleration and transport. We describe GRIPS' first Antarctic long-duration flight in December 2015 and report preliminary calibration and science results.

Electron and ion dynamics, particle abundances and the ambient plasma conditions in solar flares can be understood by examining hard X-ray (HXR) and gamma-ray emission (20 keV to 10 MeV). Enhanced imaging, spectroscopy and polarimetry of flare emissions in this energy range are needed to study particle acceleration and transport questions. The GRIPS instrument is specifically designed to answer questions including: What causes the spatial separation between energetic electrons producing hard X-rays and energetic ions producing gamma-ray lines? How anisotropic are the relativistic electrons, and why can they dominate in the corona? How do the compositions of accelerated and ambient material vary with space and time, and why?

GRIPS' key technological improvements over the current solar state of the art at HXR/gamma-ray energies, the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI), include 3D position-sensitive germanium detectors, (3D-GeDs) and a single-grid modulation collimator, the Multi-Pitch Rotating Modulator (MPRM). The 3D-GeDs have spectral FWHM resolution of a few hundred keV and spatial resolution <1mm3. For photons that Compton scatter, usually >150 keV, the energy deposition sites can be tracked, providing polarization measurements as well as enhanced background reduction through Compton imaging. Each of GRIPS' detectors has 298 electrode strips read out with ASIC/FPGA electronics. In GRIPS' energy range, indirect imaging methods provide higher resolution than focusing optics or Compton imaging techniques. The MPRM grid-imaging system has a single-grid design which provides twice the throughput of a bi-grid imaging system like RHESSI. The grid is composed of 2.5cm deep tungsten-copper slats, and a quasi-continuous FWHM resolution from 12.5–162 arcsecs is achieved by varying the grid pitch between 1–13mm. This angular coverage is capable of imaging the separate magnetic loop footpoint emissions in a variety of flare sizes. In comparison, RHESSI's 35-arcsec resolution at similar energies makes the footpoints resolvable in only the largest flares.

9905-95, Session 19

First measurement of the polarisation asymmetry of a gamma-ray beam between 1.7 to 74 MeV with the HARPO high preformance TPC telescope

Philippe Gros, Lab. Leprince-Ringuet (France)

Current gamma-ray telescopes suffer from a gap in sensitivity in the energy range between 100keV and 100MeV, and no polarisation measurement has ever been done on cosmic sources above 1MeV.

Past and present electron-positron pair telescopes are limited in the lower energies by the multiple scattering of the electrons in passive tungsten converter plates.

This results in low angular resolution, so that the sensitivity to point sources drops below 1GeV.

The polarisation information, which is carried by the azimuthal angle of the conversion plane, is lost for the same reasons.

HARPO is an R&D program to characterize the operation of a gaseous detector (Time Projection Chamber or TPC) as a high angular-resolution and sensitivity telescope and polarimeter for gamma-rays from cosmic sources.

It represents a first step towards a future space instrument.

We built and characterised a 30cm cubic demonstrator [SPIE 91441M], and put it in a polarised gamma-ray beam at the NewSUBARU accelerator in Japan in November 2014.

Data were taken at different photon energies from 1.7~MeV to 74~MeV, and with different polarisation configurations.

I will describe the full experimental setup, and in particular the dedicated triggering system.

I will describe the software I developped to reconstruct the photon conversion events, especially for low energies.

Finally I will present the performances of the detector as extracted from this analysis and preliminary measurements of the polarisation asymmetry.

Our beam-test qualification of a gas TPC prototype in a gamma-ray beam could open the way to high-performance gamma-ray astronomy and polarimetry in the MeV-GeV energy range in the next future.

9905-96, Session 19

Compton-pair production gamma-ray telescope (ComPair): a wide field discovery mission for the MeV band

Julie McEnery, NASA Goddard Space Flight Ctr. (United States)

The MeV domain is one of the most underexplored windows on the Universe, mainly due to the challenging nature of the measurements. This is an energy range of transition in the Universe. Thermal sources dominate at lower energies, while non-thermal phenomena prevail at higher energies. In addition, observations at both gamma-ray and hard X-ray energies provide compelling evidence of astrophysical objects whose radiative output peaks in the MeV range. Equally crucial is the strong evidence that spectral features such as breaks, turnovers, cutoffs, and temporal behavior, which are critical discriminating factors between competing physical models, occur within this energy band. In this paper we describe a wide-aperture discovery mission concept, Compton-Pair Production Space Telescope (ComPair) and discuss the science that it will address. This mission will investigate the energy range from 200 keV to >500 MeV with good energy and angular resolution and with sensitivity approaching a factor of 20-50 better than previous instruments.

Conference 9906: Ground-based and Airborne Telescopes VI

Sunday - Friday 26–1 July 2016

Part of Proceedings of SPIE Vol. 9906 Ground-based and Airborne Telescopes VI

9906-1, Session 1

Upgrade of the HET segment control system utilizing state-of-the-art decentralized and embedded system controllers

Marco H. Häuser, Josef Richter, Univ.-Sternwarte München (Germany); Hermanus Kriel, Amanda Turbyfill, Michael H. Ward, The Univ. of Texas at Austin (United States)

Together with the ongoing major instrument upgrade of the Hobby-Eberly Telescope (HET), we present the planned upgrade of the HET Segment Control System (SCS) to SCS2. Because HET's primary mirror is segmented into 91 individual 1-meter hexagonal mirrors, SCS is essential to maintaining mirror alignment throughout an entire night of observations. SCS2 will complete tip, tilt and piston corrections of each mirror segment at a significantly higher rate than the original SCS. The new motion control hardware will further increase system reliability. The initial optical measurements of this array will be performed by the Mirror Alignment Recovery System (MARS) and the Hartman Extra Focal Instrument (HEFI). Once the segments are optically aligned, the electro-magnetic edge sensors give precise feedback of the segment's positions, relative to their adjacent segments. These sensors are part of the Segment Alignment Maintenance System (SAMS) and are responsible for providing information about positional changes, due to external influences, such as steep temperature changes and mechanical stress, and for making compensatory calculations, while tracking the telescope on sky. SCS2 will use the optical alignment systems and SAMS inputs to command corrections of each segment in a closed loop. The correction period will be roughly 30 seconds, mostly due to the measurement and averaging process of the SAMS algorithm.

The segment actuators will be controlled by the custom developed HET Segment Motion Controller (SMOCO). It is a direct descendant of University Observatory Munich's embedded, CAN-based system and instrument control toolkit. To preserve the existing HET software structure, each SMOCO will control two adjacent mirror segments. Unlike its progenitor, SMOCO is able to drive all six axes of its two segments at the same time. SCS2 will continue to allow for sub-arc-second precision in tip and tilt as well as sub-micro meter precision in piston. These estimations are based on the current performance of the segment support mechanics. SMOCO's smart motion control allows for on the fly correction of the move targets. Since SMOCO uses state-of-the-art motion control electronics and embedded decentralized controllers, we expect reduction in thermal emission as well as less maintenance time.

HET SCS2 will be built in a close collaboration of the University of Munich's Observatory (USM), which is part of the HET collaboration and the University of Texas at Austin's HET staff. The system is currently under internal design review and still needs final approval.

9906-2, Session 1

W. M. Keck Observatory primary mirror segment repair project: overview and status

Robert L. Meeks, Steven Doyle, James Higginson, John S. Hudek, William Irace, Dennis McBride, Michael L. Pollard, Kuochou Tai, Tod Von Boeckmann, Leslie Wold, Truman Wold, W. M. Keck Observatory (United States)

The W. M. Keck Observatory Segment Repair Project is repairing stress-induced fractures near the mirror support points in the primary mirror segments. The cracks are believed to result from deficiencies in the original design and implementation of the adhesive joints connecting the Invar support components to the Zerodur mirror. Stresses caused by temperature cycling over 20 years of surface drove cracks that developed at the glass-metal interfaces.

Over the last few years the extent and cause of the cracks have been studied, and new supports have been designed. The Segment Repair Project is tasked with repairing the cracks at the segment supports and returning the segments to their current in-service performance in terms of wavefront error with less than 15 nm rms degradation. Repair of the damaged glass required development of specialized tools and procedures. Maintaining the optical performance required analysis, including large scale finite element method, of the effects of modifying the supports which are bonded at different locations from the originals. Metrology procedures using a laser tracker were developed to precisely align the support assembly hardware in order to achieve the desired optical performance. Numerous tests and trials were performed on samples and a Zerodur mock-up of a segment. Repair of the first segment (the "Pathfinder") was intended to demonstrate and fine-tune the new tools and processes.

The repair process evolved into several steps: (1) transport of the segments between the summit of Maunakea and our repair facility; (2) pre-repair metrology to establish the initial condition of the assembly; (3) removal of support hardware assemblies; (4) removal of the original epoxy bonded supports; (5) grinding and re-surfacing the damaged glass areas; (6) etching to remove sub-surface damage; (7) bonding new supports; (8) re-installation of support assemblies; and (9) post-repair metrology to return the support assembly to the precise desired positions. In order to evaluate the optical performance, both before and after on-sky measurements were made, the results of which were well within the specified requirements.

Based on this success, a three-station production repair facility is being built at the Keck Headquarters in Waimea for repairing the remaining segments beginning in summer 2016. Repairs will be performed in Waimea because more space is available and it is more convenient and efficient to work there. This requires the segments be routinely transferred from the summit to Waimea for repair then back to the summit. A custom transportation system was conceptualized, designed, built and tested to safely carry the mirror segments down the rough roads from the summit.

This paper summarizes the repair process, on-sky results, transportation system, and repair facility and also provides an update on the project status and schedule for repairing all 84 mirror segments. Strategies for maintaining quality and ensuring that repairs are done consistently are also presented.

9906-3, Session 1

A new two path shaper and feedforward control architecture for the Keck telescopes

Peter M. Thompson, Systems Technology, Inc. (United States); Tomas Krasuski, Kevin Tsubota, Shui Hung Kwok, John Fumo, W. M. Keck Observatory (United States)

A new mount control architecture has been successfully implemented at the W. M. Keck Observatory as part of a project to upgrade the control systems of both telescopes. This new control architecture is providing improved tracking and reduced settling times after small repositioning moves. Two major changes were made to the control system's design: (1) new digital structural filters implemented using an FPGA, which reduce the excitation of the structural modes and allow higher velocity loop gains

while maintaining the required gain and phase margins for velocity loop stability, and (2) a two-path command shaping and feedforward system built around the position loop controller, which provides more control over the shape of the command response and reduced overshoot in response to short moves. This architecture was integrated with a new pointing model, new position encoders, and new tilt meters (all part of the control system upgrade). The improvements to settling time for short moves and improvements to tracking accuracy, especially at high tracking rates, are presented. A discussion on algorithms for streamlining the tuning of the velocity loop and feedforward filter coefficients is included.

9906-4, Session 1

MSE observatory upgrade: a revised and optimized astronomical facility

Steven E. Bauman, Greg Green, Kei Szeto, Canada-France-Hawaii Telescope (United States)

The Canada France Hawaii Telescope Corporation (CFHT) plans to repurpose its observatory on the summit of Maunakea and operate a ~10 m (effective aperture) wide field spectroscopic survey telescope, the Maunakea Spectroscopic Explorer (MSE). MSE will reuse the CFHT site and build upon the existing observatory infrastructure, facilities, processes, and expertise, while minimizing environmental impact on the summit. Central themes of the development plan are reusing and upgrading wherever possible.

The CFHT site has some of the best seeing in the northern hemisphere. MSE will upgrade the facility with a larger aperture telescope and equip it with dedicated instrumentation to better utilize the site and offer the ability to do transformative science to its users. The knowledge and experience of the current CFHT staff will contribute greatly to the engineering of this new facility.

MSE will use the same building and telescope pier as CFHT. It will be necessary to replace the current dome since a larger slit opening is needed for a larger telescope. Once the project is completed the new facility will be almost indistinguishable on the outside from the current CFHT observatory. MSE will build upon CFHT's pioneering work in remote operations, with no staff at the observatory during the night, and use modern technologies to reduce daytime maintenance work.

MSE will require structural support upgrades to the building to meet building seismic code requirements and accommodate a new larger telescope and upgraded enclosure. Additional radial bracing will be added to support the outer azimuth ring girder and lateral buckling restraint bracing will replace the current 1st, 2nd, and 3rd floor perimeter bracing. All structural modifications will be implemented from inside the building to minimize disturbances to the summit environment.

MSE will use a thermal management system which removes heat loads from the building, flushes excess heat from lower levels, and maintains the observing environment temperature. The existing building exhaust tunnels in the basement will continue to be used to remove heat loads deliberately positioned in the basement and minimize thermal loads from the building and enclosure environment. Remaining heat will be flushed from the lower levels prior to reaching the observing environment using a passive ventilation system. An active cooling system will be used to keep large structures near the ideal nighttime observing temperatures.

This paper describes the design approach for redeveloping the CFHT facility for MSE including the infrastructure and equipment considerations required to support and facilitate nighttime observations. The building will be designed so existing equipment and infrastructure can be reused wherever possible while meeting new requirements. Past experience and lessons learned will be used to create a modern, optimized, and logical layout of the facility.

9906-5, Session 1

The Hobby-Eberly Telescope wide-field upgrade

Gary J. Hill, Niv Drory, John M. Good, Hanshin Lee, Brian L. Vattiat, The Univ. of Texas at Austin (United States); Hermanus Kriel, The Univ. of Texas at Austin (United States) and Hobby-Eberly Telescope (United States); Jason Ramsey, The Univ. of Texas at Austin (United States); Randy Briant, Hobby-Eberly Telescope (United States); Linda Elliot, The Univ. of Texas at Austin (United States); James R. Fowler, Hobby-Eberly Telescope (United States); Martin Landiau, Ronnie Leck, The Univ. of Texas at Austin (United States); Stephen C. Odewahn, Hobby-Eberly Telescope (United States); David Perry, Richard Savage, The Univ. of Texas at Austin (United States); Emily Schroeder Mrozinski, Matthew Shetrone, George Damm, Hobby-Eberly Telescope (United States); Karl Gebhardt, The Univ. of Texas at Austin (United States); Jerry Martin, Hobby-Eberly Telescope (United States); Taft E. Armandroff, The Univ. of Texas at Austin (United States); Lawrence W. Ramsey, The Pennsylvania State Univ. (United States)

The Hobby-Eberly Telescope (HET) is an innovative large telescope, located in West Texas at the McDonald Observatory. The HET operates with a fixed segmented primary and has a tracker, which moves the four-mirror corrector and prime focus instrument package to track the sidereal and non-sidereal motions of objects. We have completed a major multi-year upgrade of the HET that has substantially increased the pupil size to 10 meters and the field of view to 22 arcminutes by replacing the corrector, tracker, and prime focus instrument package. The upgraded wide field HET will feed the revolutionary new integral field spectrograph called VIRUS, in support of the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX), a new low resolution spectrograph (LRS2), an upgraded high resolution spectrograph (HRS2), and later the Habitable Zone Planet Finder (HPF). The upgrade is being commissioned and this paper discusses the commissioning process and performance of the new HET.

9906-6, Session 2

Chinese Large Aperture Optic-IR ground-based telescope: planning for next decade *(Invited Paper)*

Dingqiang Su, Nanjing Univ. (China); Ming Liang, National Optical Astronomy Observatory (United States); Xiangyan Yuan, Hua Bai, Bozhong Gu, Xiangqun Cui, Nanjing Institute of Astronomical Optics & Technology (China)

The twelve meters optical telescope has put forwarded in China recently. It is considered as a general purpose optical telescope with three parts: wide field prime focus for imaging and spectroscopic survey, Nasmyth focus for high resolution observations of many instruments, and coude focus for interferometry and extremely accurate instruments. In above three parts there are important innovations or the better design results than other telescopes. The optical systems, structure, fan-shaped segmented primary mirror, and the innovations, design results are presented in this invited talk.

9906-7, Session 2

Mayall telescope control system modernization: design, implementation, and performance

David Sprayberry, Patrick Dunlop, Matthew Evatt, Larry Reddell, National Optical Astronomy Observatory (United States); Shelby Gott, John Donaldson, Robert J. Stupak, Robert Marshall, Behzad Abareshi, Deanna Stover, National Optical Astronomy Observatory (United States); Michael Warner, Rolando E. Cantarutti, National Optical Astronomy Observatory (Chile); Ronald G. Probst, National Optical Astronomy Observatory (United States)

The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14000 sq. deg. will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs. Motivated both by a desire to improve the Mayall's pointing and tracking performance prior to the start of the DESI installation and by a need to improve the maintainability of the Telescope Control System, we recently completed a major modernization of that system. The changes to the Mayall drew heavily from the servo designs and implementation developed for its sister telescope, the CTIO Blanco 4-meter, as described by Warner, et al (2012), SPIE 8451-29. Reusing as much of their work as possible enabled our project to be completed in less than one year. We describe here the things we did differently from the Blanco upgrade, either because of mechanical challenges specific to the Mayall, or because of the different higher-level software environment that has evolved at the Mayall over the years. We also present results from the as-built performance of the new servo and pointing systems, showing the dramatic improvements from the old system to the new.

9906-8, Session 3

The Large Millimeter Telescope (LMT): project status, early science, and operational performance *(Invited Paper)*

David H. Hughes, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); F. Peter Schloerb, Univ. of Massachusetts Amherst (United States); Alberto Carramiñana, Miguel Chávez Dagostino, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Min S. Yun, Grant W. Wilson, Gopal Narayanan, Neal Erickson, Univ. of Massachusetts Amherst (United States); Arak Olmos Tapia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); David R. Smith, MERLAB, P.C. (United States); Kamal Souccar, Univ. of Massachusetts Amherst (United States); David M. Gale, José Luis Hernández Rebollar, César E. Cuevas-Arteaga, Alfredo Montaña, Daniel Ferrusca Rodriguez, Milagros Zeballos, David Sánchez-Argüelles, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

The Large Millimeter Telescope (LMT) Alfonso Serrano is a bi-national (Mexico & USA) telescope facility operated by the Instituto Nacional de Astrofisica, Optica y Electronica (INAOE) and the University of Massachusetts. The LMT is designed as a 50-m diameter single-dish millimeter-wavelength telescope that is optimized to conduct scientific observations at frequencies between ~70 and 350 GHz. The LMT is constructed on the summit of Sierra Negra at an altitude of 4600m in the Mexican state of Puebla. The site offers excellent mm-wavelength atmospheric transparency all-year round, and the opportunity to conduct submillimeter wavelength observations during the winter months. Following first-light observations in mid-2011, the LMT began regular scientific operations in 2014 with a shared-risk Early Science observing program using the inner 32-m diameter of the primary reflector with an active surface control system. The LMT has already performed successful VLBI observations at 3mm with the High Sensitivity Array and also at 1.3mm as part of the Event Horizon Telescope. The LMT will enter full scientific operations as a 50-m diameter telescope in early 2017, making it the world´s largest single-dish telescope operating at 1.1mm. I will describe the current status of the telescope project, including the early scientific results, as well the instrumentation development program, the plan to improve the overall performance of the telescope, and the on-going transition towards the formation of the LMT Observatory to support the scientific community in their use of the LMT to study the formation and evolution of structure at all cosmic epochs.

9906-9, Session 3

Atmospheric seeing measurement from bright star trails with frame transfer CCDs

Bin Ma, National Astronomical Observatories (China); Zhaohui Shang, Tianjin Normal Univ. (China); Yi Hu, National Astronomical Observatories (China)

We present a new application of frame transfer Charge-Coupled Device (CCD) on measuring atmospheric seeing.If a telescope is equipped with a shutterless, frame transfer CCD camera, a bright star will generate a trail during the frame transfer phase. Because the transfer is very fast, the trail is a series of short exposures (~ 1 ms) of the target star. Therefore the centroid is jittery due to atmospheric turbulence, and the amplitude can be utilized to derive astronomical seeing. We present the preliminary results from STA1600FT CCD on Antarctic Survey Telescopes (AST3) tested in China and Antarctica.

Atmospheric seeing is one of the key site parameters for the optical/IR observatories, because it limits the spatial resolution of large aperture telescopes. The best median seeing of ground-base site was 0".27, which was measured at Dome C, Antarctica. Dome A is expected to have similar or even better seeing for its extremely low boundary layer, however, there has not been direct seeing measurement during polar night yet. Because it is unattended all the year except a 20-day expedition, the widely used seeing measurement instruments, such as DIMM (Differential Image Motion Monitor), MASS (Multi-Aperture Scintillation Sensor), are hard to be operated at Dome A automatically. This new method enables us to estimate seeing with an existing telescope and CCD camera.
AST3 is an array of three 50/68 cm modified Schmidt telescopes, and equipped with 10560 x 10560 STA1600FT CCD cameras. The cameras have no shutter,instead they work in frame transfer mode to terminate the exposure. During the frame transfer, the pixels where a star is located keep collecting photons of the star, but the charges are transferred to the adjacentpixels every time when vertical shift occurs. Finally this generates a bright trail along the readout direction for a bright star, and the horizontal positions of the trail varies randomly due to atmospheric turbulence.We show the random motion in the trail, estimate seeing, and compare it with the results from simultaneous DIMMobservations when AST3-2 was tested in Mohe, China.The trend oftrail seeing agrees well with DIMM seeing, while more careful calibration is still necessary because of AST3's larger aperture than the Fried parameter r0. In addition, benefitting from its ~3x1.5 square degree wide field-of-view, AST3 is able to capture multi bright stars simultaneously, whose separations can be from sub-arcmin to degrees. Their trails offer an excellent opportunity to investigate turbulences with angular distance much larger than the isoplanatic angle, which is usually on the order of several arcsecs.

9906-10, Session 3

Sutherland site characterization and prospects of an AO system for SALT

Laure Catala, Univ. of Cape Town (South Africa) and South African Astronomical Observatory (South Africa); Steven M. Crawford, David A. H. Buckley, South African Astronomical Observatory (South Africa)

As part of future plans to improve the performances and increase the competitivity of the Southern African Large Telescope (SALT), we have been looking at possible ways of implementing an adaptive optics (AO) system as part of the second generation of instruments. In this framework, we conducted a 5 year long atmospheric turbulence characterization at the Sutherland site, measured the overall effects of the telescope structure on optical performance, and carried out detailed simulations of the performance of an AO system on SALT.

This study produced realistic and up-to-date seeing values, atmospheric turbulence profiles as well as specific site characteristic and patterns that were used to feed AO simulations. We found a median seeing seeing value of 1.49". And it appears that the 2 main contributors to the turbulence are the ground layer turbulence below 100 m and around 300 m, and to a lower extent the wind shear layer around 3 km. Also the winter months show worse seeing conditions than average, this is due to predominant East, South-easterly winds associated with degraded seeing conditions.

Moreover, as part of the overall study, we tested dome seeing measurements with the Berkley Visible Imaging Tube (BVIT) instrument on SALT as well as analyzing the overall performance of the image quality for SALT. BVIT is a visible photon counting detector designed for high time resolution astronomy, with 25 ns time precision. Using the SALT segmented primary mirror in burst mode as an Hartmann mask and the fast imaging capabilities of BVIT we created the equivalent of a Shack-Hartmann wavefront sensor that we used for seeing measurements.

Our SALT AO simulations were based on the results from the site characterization along with SALT design specificities, including its prime focus tracker leading to pupil size and shape variations. We used the software PAOLA to determine the optimum general parameters of an AO system on SALT in the case of natural guide star (NGS), taking into account performances and sky coverage. We then use those system parameters to look at the possible improvement in spectroscopic performances for different conditions of seeing, wavelength, slit/fiber size and NGS magnitude and off-axis angle.

We present here, the results from the Sutherland site characterization and our BVIT experiment project as well as the SALT AO simulations and their consequences in the prospect of the future design of an AO system on SALT.

9906-11, Session 4

Design solutions for dome and main structure (mount) of giant telescopes

Armando Bilbao, Gaizka Murga, Alberto Vizcargüenaga, IDOM Ingenieria y Consultoria S.A. (Spain)

During the last recent years, designs for several giant telescopes ranging from 20 to 40m in diameter are being developed: European Extremely Large Telescope (E-ELT), Giant Magellan Telescope (GMT) and Thirty Meter Telescope (TMT).

It is evident that simple direct up-scaling of solutions that were more or less successful in the 8 to 10m class telescopes can not lead to viable designs for the future giant telescopes. New solutions are required to provide adequate load sharing, to cope with the large-scale derived deflections and to provide the required compliance, or to respond to structure-mechanism control interaction issues, among others.

From IDOM experience in the development of the Dome and Main Structure of the European Extremely Large Telescope and our participation in some other giant telescopes, this paper reviews several design approaches for the main mechanisms and key structural parts of enclosures and mounts/main structures for giant telescopes, analyzing pros and cons of the different alternatives and outlining the preferred design schemes.

The assessment is carried out mainly from a technical and performance-based angle but it also considers specific logistical issues for the assembly of these large telescopes in remote and space-limited areas, together with cost and schedule related issues.

9906-12, Session 4

Holographic beam mapping of the CHIME pathfinder array

Philippe Berger, Univ. of Toronto (Canada)

The Canadian Hyrodgen Intensity Mapping Experiment (CHIME) is a new transit interferometer currently being deployed at the Dominion Radio Astrophysical Observatory (DRAO) in Penticton, British Columbia. We have built and deployed the CHIME Pathfinder, a smaller, 2-cylinder test-bed which has been instrumented with 128 dual polarisation dipole antennas and a custom correlator and is currently surveying the Northern hemisphere in 1024 frequency bands between 400-800 MHz. In this paper, we describe the holography instrument and technique we are employing to characterize the radiation pattern for each of the Pathfinder's 256 inputs.

CHIME's frequency band is chosen to correspond to the redshifted 21 cm line emission of neutral hydrogen (HI) at redshifts 0.8–2.5. It's angular resolution is designed for intensity mapping of the large scale distribution of HI across this largely unexplored redshift range and targeted to measure the Baryon Acoustic Oscillation scale. The results will provide constraints on the time evolution of dark energy, including the moment it begins to dominate the energy density of the universe. To do so, we must contend with astrophysical foregrounds, notably the synchrotron emission of the Milky Way, which are some five orders of magnitude brighter than the HI signal. Detailed characterisation of the polarised telescope beam is crucial to the foreground cleaning process, preventing the bleeding of angular structure in to the frequency direction or "mode mixing" and leakage of polarised signal into total intensity.

The John A. Galt telescope is an equatorial mounted 26 meter diameter parabolic telescope also located at the DRAO. We have equipped it with a separate 400-800 MHz instrument which is fed into the CHIME Pathfinder correlator, allowing cross-correlation of its signal with the rest of the array. By tracking point sources with the 26m as they slice through the CHIME beam, we map the polarised beams of the CHIME pathfinder, a technique known as holography. This allows for high signal-to-noise measurements of all 256 beams in both amplitude and phase. We report the status of the holography instrument and initial results of this effort.

9906-13, Session 4

A survey of enclosure suspension and rotation systems for 3-15m telescopes

Bruce C. Bigelow, GMTO Corp. (United States); Nathan P. Loewen, Emile van Vuuren, Sightline Engineering Ltd. (Canada); William S. Burgett, GMTO Corp. (United States)

The enclosure suspension and rotation systems for the next generation of Extremely Large Telescopes (ELTs) will carry structures that are 2-3 times larger in diameter, and 5-10 times heavier than those for the last generation of 6-10m optical/infrared telescopes. The enclosure rotation and suspension systems can present single-point failure modes for an observatory, so the requirements on reliability, availability, and

maintainability increase with increasing telescope size (and cost). We report here on a survey of several optical, infrared, and sub-millimeter telescope enclosures, considering the key design features of the suspension and rotation systems, including wheel and track geometry, details of the wheel/track interface, number of wheels per bogie, average load per wheel, rotation drive method, etc. We outline some of the key decisions and design choices to make during the development of enclosure suspension and rotation systems, and a logical process for defining those systems based on the architecture of the enclosure.

9906-14, Session 4

Performance of cable isolators in the transport of large optical assemblies

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Following a 7-year, multi-million dollar effort to fabricate a 730 kg, 4 element Wide Field Corrector (WFC) for the Hobby-Eberly Telescope (HET) Wide Field Upgrade (WFU), it needed to be transported 820 km to its destination at the McDonald Observatory in West Texas. Alignment tolerances for individual mirrors in the assembly were in the 5 um range. Due to the size and mass and ultimate destination of the payload, the only option available for transport was via roadway on a flat-bed trailer. While the route was primarily interstate highway, it presented a great variety of vibrational inputs due to poor paving conditions, and mountain roadways. Consideration also had be given to avoiding high ambient temperatures. Early in the design of the corrector assembly it was assumed that cable isolators would be the key element to isolate the payload from vibrational inputs, however, few documented references were available to provide the assurances required for transporting a load so key to the success of the telescope program. Tests were designed to simulate the load conditions and inputs and outputs to the test load were measured for verification of the isolator performance. This was followed up with monitoring of vibration throughput during the actual shipment of the WFC. Upon arrival at the destination, the alignment of the assembly was checked and found to have no appreciable change in the alignment. Data and lessons learned are presented on the performance of air-ride trailers as well as the performance of cable isolators.

9906-15, Session 5

SRT as a receiver in bistatic radar space debris observations

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The Sardinia Radio Telescope (SRT) is a fully steerable antenna with a Gregorian optical configuration, equipped with a 64 meters diameter shaped primary mirror with a focal length to diameter ratio (f/D) of 0.33. The antenna is managed by INAF (National Institute for Astrophisics) and by ASI (Italian Space Agency) with the aim of using it for radio astronomical and for spatial observations. The time allocated to ASI is used to perform space debris observations and deep space down link data reception. The antenna has three focal positions, one in the primary, one for the Gregorian and two in the Beam Waveguide. In the primary focus, the SRT has a cryogenic cooled dual band L-P receiver designed to perform radio astronomical observations. Recently we have been involved in performing some space debris radar observation at P band in a bistatic configuration, receiving the echo diffused from few well known space debris illuminated with an Italian Air Force transmitter located in Sardinia. In this first tests we made different observation of space debris in parking mode which means by pointing the transmitter and the receiver in the same space region where we know the transit of a catalogued space debris. The transmitting antenna was switched on at 410 MHz in a CW (continuous wave) mode for few seconds during which the SRT was pointed in the same direction to receive with the P band receiver the small diffused signal. The radar transmitter has a 4kW emitting power and a small aperture antenna, with a beam of about 30°, much wider than the 0.8° HPBW of the SRT at the same frequency. During the CW transmission of the radar, due to the 30 km short line of sight distance between the SRT and the transmitter, we were able to receive not only the diffuse signal by the space debris, but also the direct powerful signal emitted by the antenna transmitter, pointed in the sky direction. In this way, while waiting for the diffused signal from the debris, we were also sure that the transmitter started to emit and was well working. As a back end we used a spectrum analyzer, with a Labview© control software, centered at a frequency of 410 MHz and with a very narrow frequency span and low resolution bandwidth, in order to be able to visualize the Doppler frequency shifted by the space debris. We performed different observing campaigns during which we were able to receive the echoes of debris of different RCS (Radar Cross Sections) from which we could measure the frequency Doppler shift and so the velocity of the debris. Due to the low flexibility and programmability of the SA, we decided to develop a new back end specifically designed for space debris observations, based on the ROACH (Reconfigurable Open Architecture and Computing Hardware, FPGA-based) and a GPU-based PC. In this article we will show the results of this preliminary SRT space debris observations and back end development.

9906-16, Session 5

On preparing UKIRT to observe satellites and orbital debris

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For 35 years the United Kingdom Infrared Telescope has provided exquisite infrared astronomical data from the summit of Mauna Kea on the big island of Hawaii. The observatory operates an assortment of instruments that allow the collection of photometric, spectroscopic and polarimetric measurements of astronomical objects across a wavelength band of 1 to 25 microns. This covers the Y,Z,J,H,K,L,M,N and Q bands of IR astronomy. In addition R band photometry can be acquired via the telescope guider.

In 2013 the process of developing an Orbital Debris and Satellite observation capability for the United Kingdom Infrared Telescope was initiated. This process involved the modification of various operational aspects of the observatory. For example a system for converting orbital object two line elements into telescopes pointing position with rates was necessary. Data pipeline modifications were also necessary to account for the differences between typical astronomical data and the orbital debris and satellite data. There was also a shift in observing philosophy for orbital debris and satellite observations. Whereas a typical night in an astronomical observatory can involve the observation of 10's or 100's of objects, a night of orbital debris and satellite observations might only involve the observation of one object and various calibration standards.

After a year of implementing modifications the observatory became capable of providing deep space observations of orbital debris and satellites in a queue based format. The telescope has been operating with this capability for the past 2.5 years and has generated terabytes of observational data of orbital debris and satellites that are in the GEO belt distributed across the Pacific Ocean.

This paper will discuss the steps that were required to implement a GEO belt object observing capability at the UKIRT observatory. Representative photometric and spectroscopic data will be presented for a variety of orbiting objects.

9906-87, Session PS1

Network management plan for SKA

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The SKA Observatory will be the largest astronomy facility in the world. It will be composed of the SKA1-Mid telescope in South Africa, and SKA1-Low in Australia, with the General HQ in UK, and local headquarters in the host countries. The SKA1-Mid is formed by an array of 190 dishes, and the SKA1-Low is an aperture array with 512 stations of 131072 antennas in total. Both arrays will contain a massive number of components that need to be connected to a shared data network to allow the operation of SKA. To ensure the interoperability of the different elements in SKA a Network Management Plan is key. In this contribution we present an outline of this plan, and the challenges that it will try to overcome.

9906-88, Session PS1

Prefocal station mechanical design concept study for the E-ELT

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The E-ELT will host one Prefocal Station on each of its two Nasmyth platforms. The main functional requirements of these units are to provide a focal plane to any of three Nasmyth focal stations & one Coudé focus, optical sensing to support telescope low order optimisation and seeing limited image quality, and optical sensing to support characterising and phasing of M1 and other telescope subsystems. The Prefocal Stations will also provide a reference for aligning the Nasmyth instruments. The Prefocal Station User Requirements are being used to derive the Prefocal Station Technical Requirements Specification that will form the basis for the detailed design, development and production of the system. This specification process includes high-level architectural decisions and technical performance budget allocations. The concept mechanical design studies reported here have been performed in order to validate key system specifications and their associated technical budgets. The main subsystems of the Prefocal Station A are described in the breakdown below:

Sensor arms: The current baseline requires the use of 3 sensor arms for the telescope wavefront sensors. This requires the use of three independent arms, capable of moving within the patrol area. They carry the necessary optics and cameras to carry out the telescope wavefront sensors functions.

Cable wrap: Due to the limited space and mass constraints a proof of concept design of the cable wrap has also been developed. This needs to feed the three independent sensor arms with their necessary cables and cooling. In this concept there is a main wrap that carries all the necessary cables and cooling using a classical loop design onto the unit. The cables are then split into the necessary three groups and are passed through separate secondary wraps. These secondary wraps act in the same plane as each other. The main wrap then provides 540° of rotation.

M6N fold mechanism: The M6N fold mechanism needs to feed light into either of the two lateral science ports with minimal vignetting of the patrol area for the TWS. It is deployable in and out of the beam to allow a straight through science focus. The concept design has considered the accurate positioning of the fold mirror to meet the focal plane position error budgets, its Eigen frequencies, its mass and minimising its vignetting profile to provide sufficient field past it for the TWS.

M6C Coudé flat: The Coudé flat mechanism is a small deployable flat used to feed science light to the Coudé focal train. As with the larger M6N fold mechanism, its vignetting profile is minimised.

Supporting structure: This is a large steel framework (5m x 4.75m x 10m) that carries all the above sub-units. It has conflicting requirements for stiffness vs mass (which is quite challenging – especially when considering earthquake loads). It provides the interface to the Nasmyth platform.

Phasing Station: Provides optical sensing to characterise M1 and support mirror segment phasing and to correct high order figure errors such as scalloping.

Auxiliary equipment: Safe working platforms and ladders for maintenance, access, and covers.

9906-90, Session PS1

1.2m astronomical telescope for space-to-ground quantum communication experiment

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Quantum Key Distribution (QKD), the fastest growing and most technologically sophisticated quantum communication technology, has become the pioneer in the future practical quantum communications because of its unconditional security guaranteed by basic principles of quantum mechanics. Chinese Academy of Sciences has plans to launch quantum science experiment satellite in the near future, a series of quantum communication experiments can be done through this satellite. The success of the experiment depends on the continuous tracking and pointing between the optical ground station(OGS) and onboard communication terminal. This paper describes the equipment and features of the 1.2m astronomical telescope which will perform experiments with quantum experiment satellite of China. The optical ground station uses 1.2m gimbaled telescope to collect the photons, the strategy of the system is slightly developed to meet the need of tracking LEO satellite?which has coarse and fine loop, and it can control a transmitting and receiving laser beam within a few micro radians jitter. This telescope with multiple functions will play an important role in space-to-ground quantum communication.

9906-91, Session PS1

Mauna Kea Spectroscopic Explorer design development from feasibility concept to baseline design

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The Maunakea Spectroscopic Explorer (MSE) is designed to be the largest non-ELT optical/NIR astronomical telescope, and will be a fully dedicated facility for multi-object spectroscopy over a broad range of spectral resolutions. The MSE design has progressed from feasibility concept into its current baseline design where the system configuration of main systems such as telescope, enclosure, summit facilities and instrument are fully defined. This paper will describe the engineering development of the main systems, and discuss the trade studies to determine the optimal telescope and multiplexing designs and how their findings are incorporated in the current baseline design.

9906-92, Session PS1

The DAG project, a 4m-class telescope: the rotating enclosure performances

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DAG (Dogu Anadolu Gözlemevi, Eastern Anatolia Observatory) is a project fully funded by Turkish Ministry of Development and the Atatürk University of Astrophysics Research Telescope - ATASAM.

DAG will be a 4m class optical and infrared telescope and will be installed at an altitude of 3170m asl on the Erzurum Plateau, near the town of Erzurum, Eastern Anatolia, Turkey.

EIE GROUP - Venice, Italy was awarded the contract for the construction of the DAG D, last October 2015.

The design of the Rotating Enclosure fits in the TBO Program which aims at developing a Dome /Telescope systemic optimization process for both performances and competitive costs, based on previous project commitments like NTT, VLT, VST and VISTA.

The Enclosure will provide wind and other environmental conditions protections for the Telescope. The main characteristics of the Enclosure are: a light structure and a specific cladding system, a modular windscreen with fixed permeability and a ventilation door system, to allow the air flushing and temperature control during the Telescope observation.

9906-93, Session PS1

DEdicated MONitor of EXotransits and Transients (DEMONEXT): a low-cost robotic and automated telescope for followup of exoplanetary transits and other transient events

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We present the design and development of the rebuilt and recommissioned 20'' DEMONEX telescope, now known as DEMONEXT, an automated and robotic telescope jointly funded by The Ohio State University and Vanderbilt University. The telescope is a PlaneWave CDK20 f/6.8 Corrected Dall-Kirkham Astrograph telescope on a Mathis Instruments MI-750/1000 Fork Mount located at Winer Observatory in Sonoita, AZ. The new DEMONEXT has a Hendrick electronic focuser, FLI CFW-3-10 filter wheel, and a 2048x2048 pixel FLI Proline CCD3041 camera with a pixel scale of 0.89'' per pixel and a 30.5' Field-of-View. The telescope's automation, controls, and scheduling are implemented in Python, including a facility to add new targets in real time for rapid follow-up of time-critical targets. DEMONEXT will be used for the confirmation and detailed investigation of newly discovery planet candidates from the KELT survey telescope, exploration of planet atmosphere transmission studies, and monitoring of select eclipsing binary star systems as benchmarks for models of stellar evolution. DEMONEXT will enable rapid confirmation imaging of supernovae, flare stars, active galaxy tidal disruption events, and other transients discovered by the ASAS-SN survey telescopes. DEMONEXT will also provide follow-up observations of single-planet transits discovered by the upcoming TESS mission, and to investigate long-period eclipsing systems discovered by GAIA.

9906-94, Session PS1

The University of Tokyo Atacama Observatory 6.5m Telescope: enclosure design and wind analysis

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We present preliminary results from our wind studies on the enclosure design for the University of Tokyo Atacama Observatory (TAO) 6.5-m telescope now being constructed at the summit of Co. Chajnantor in northern Chile (5,640-m altitude).

A detailed design of the enclosure for the TAO 6.5-m telescope is currently underway, where as a part of studies we perform unsteady computational fluid dynamics (CFD) calculations and wind tunnel experiments in order to investigate how the wind flow, which rises from the plateau at 5,000-m altitude, is disturbed topographically and blows through the summit facilities.

First, we construct a three-dimensional solid model of the whole of Co. Chajnantor (5 km on a side and a height of 800 m) by using a state-of-the-art technology in Geographic Information System (GIS).

A CFD calculation with about 20 million grid points adaptively refined (more finely spaced near the ground) reveals the wind speed to be accelerated at the summit by a factor of 1.2--1.3 compared to that at the plateau, which is in good agreement with the result of the wind tunnel experiment.

We use the resulting wind pressure (3850 N/m^2 at wind speed of 85 m/s expected at a maximum) in structural analysis of the summit facilities.

We also investigate how the wind flows around the summit facilities and make sure that there is a sufficient space between the enclosure and the adjacent operation building so that the wind flow obstructed at the operation building does not affect the flow to the enclosure.

We then use the disturbed and accelerated wind speed profile to analyze the wind flow and the distribution of air temperature around and inside the telescope enclosure in detail.

In the basic design reported in 2012, we allocated the maximum number of the ventilation windows in the enclosure: 13 windows at a level of the observing floor (hereafter VW1), 12 at a level of the telescope primary mirror (VW2), and 12 at a level of the secondary mirror (VW3).

By changing the number of windows VW3, we examine the importance of the windows VW3.

Several configuration of CFD calculations with about 90 million grid

points (finest resolution of about 15 cm inside the enclosure) represent little difference in the wind speed distribution or the distribution of air temperature.

We find that any air turbulence rising from the ground is drifted through the windows VW1 and therefore would have little influence on imaging performance of the telescope.

These facts are unchanged with changing the enclosure rotation (azimuth) angle against the prevailing wind direction, i.e. the west.

After considering operation procedures and construction costs, we decide to locate 13 windows VW1 (at a level of the observing floor), 12 VW2 (the primary mirror), and 2 VW3 (the secondary mirror).

9906-95, Session PS1

Analysis of the three-mirror systems for survey telescopes

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Survey telescopes, which are the systems with angular field up to a few degrees, are applied in several areas, not only for the astronomy, but for the weather observing, and asteroid and comet detection (ACD). Systems with relatively small diameters (up to 1,5 m) are of great interest both as ground-based and space instruments. For the best functionality telescope schemes should have small sizes, have sufficient characteristics for sky survey. It is also preferable that the systems can be manufactured by the most simple methods and facilities.

As a rule such survey systems are fast (up to F/3 ... F/1.5 and faster). Therefore, the most part of survey telescopes are reflective systems with additional lens correctors. Lens elements in these instruments can lead to some difficulties because the possibility of manufacturing of large size lens corrector of the optimal glass sort does not always exist. So from that point of view mirror systems can give some advantages. Mirror systems are also of interest due to the wide spectrum range used for operation. However, the design of the mirror system that can give both sufficient f-number and large angular field is the complicated and complex task, first of all because of difficulty during the choosing the initial principal scheme.

For the sky survey the three- and four–mirror systems can be used. The decreasing of the number of the mirrors can decrease the cost of the project, make the mechanical construction simpler, etc. To provide the wide field it's necessary to correct four aberrations (spherical aberration, coma, astigmatism and field-curvature) and the minimum number of the mirrors is three. But in the case of the three mirror systems the range of parameters, which lead to realizable systems taking into account the constructional and stray light limitations, becomes much narrower.

Using the expressions based on the third-order aberration theory the several system of survey telescopes were chosen which can provide the needed characteristics. The examples of the schemes are given, including their optical characteristics and the baffles configuration.

9906-39, Session PS2

A primary mirror metrology system for GMT

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The Giant Magellan Telescope (GMT) will consist of seven 8.4 m aperture "unit telescopes" arranged as a phased, radially symmetrical array, on a common mount. First light with a subset of four unit telescopes is currently scheduled for 2022. Installation and testing of the first M1/M2 segment pair will begin in 2021.

The project is currently considering an important aspect of the assembly, integration and verification (AIV) of the unit telescopes; a dedicated system to characterize the on-sky performance of the M1 segments, independently of the M2 subsystem. A primary mirror metrology system is proposed. The main purpose of this system will be to characterize the deflections and deformations of the M1 segment with respect to the axis of an instrument interface, as a function of gravity and temperature.

The metrology system will incorporate a small prime focus corrector, the largest optical element of which will be of the order of 150 mm diameter. The corrector can provide a small field (0.5 to 1 arc minute diameter) corrected to ~ 0.1 arc-second 80% encircled energy spot sizes. At the focal plane a linear stage will be utilized to position either a suitable imaging detector or a Shack Hartman wavefront sensor.

The prime focus camera design presented here incorporates four spherical elements of standard optical glass. The design has the advantage of being tilt insensitive; tilts of up to 0.5 degrees about the coma neutral point, near the focal plane, produce no significant aberration. On the other hand, lateral translations of 50 microns lead to an easily measureable aberration signal. These properties enable the system to determine the optical axis of the M1 segments, with respect to the corrector, to well with 50 microns in de-centre.

A 3-D metrology system (as presented in another paper in this conference) will be employed to centre the corrector with respect to the axis of a suitable instrument interface. An expected accuracy of this centering expected to be at worst 50 microns.

With the desired location of the M1 segment optical axis thus determined, and after acquiring a suitable stellar target, the system utilizing either a detector, and/or Shack Hartmann wavefront sensor, will be employed to correct the M1 segment for tilt and position. At the same time, the Shack Hartmann wavefront sensor can measure segment deformations. This exercise will be repeated at a number of Alt/Az position, and over some range of thermal conditions, enabling the production of accurate pointing models and collimation/deformation look-up tables.

The advantages of having a well-characterized M1 subsystem in advance of utilizing the M2 subsystem, have been discussed in part by Blanco (2012). A primary advantage is that with an accurate pointing model for the M1 segments already established in this way, co-linearity of the M1 and M2 segment axes can be established to a high accuracy, just by correcting both pointing and coma with M2. Other advantages include the thorough early workout of various telescope subsystems, and on a system of considerably less complexity than the final telescope/instrument configuration.

9906-40, Session PS2

GMT azimuth bogie wheel-rail interface wear study

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Performance of a rotating enclosure azimuth bogie system is vital for the operation of an observatory and as such, all components are subject to wear. The bogie design and rail interface merit a high level of scrutiny for achieving a proper balance between capital costs, maintenance costs, and the risk for downtime during planned and unplanned maintenance or replacement procedures.

To properly assess tradeoffs between various wheel-rail and roller-track interfaces, M3 Engineering & Technology Corp. (M3) and Uni-Systems Engineering (UNI) performed a comprehensive comparison study of multiple bogie wheel and rail interface alternatives, thereby allowing Giant Magellan Telescope (GMT) to make an informed decision with regards to the available options.

The paper provides information of various azimuth bogie design options studied in regards to the performance of GMT rotating enclosure. The

azimuth bogie design and rail interface merit a high level of scrutiny for achieving a proper balance between capital costs, maintenance costs, and the risk for downtime during planned and unplanned maintenance or replacement procedures.

Of particular importance is the interface between the azimuth wheels and rail, as usage frequency is high, the full weight of the rotating enclosure must be transferred through small patches of contact, and replacement of the rail would pose a greater logistical challenge than the replacement of smaller components such as bearings and gearmotors.

Regardless of the magnitude of loading, wear is an inevitable outcome of rolling and sliding contact between bodies. Even if contact stresses are, in theory, limited to the elastic regime – a highly conservative approach rarely implemented by the railway or crane industries – plastic deformation is invariably observed in rail cross sections due to microscopic asperities on the wheel and rail surfaces. Consequently, wear still occurs. From this vantage point, the design objective is not to eliminate wear from the system but, rather, to address it in an intentional manner and ensure that the anticipated wear rate meets design objectives.

9906-96, Session PS2

Real-time alignment and co-phasing of multi-aperture systems using phase diversity

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Multiple aperture systems (segmented mirrors or telescope arrays) are now an established solution to build large telescopes on ground or in space. However the alignment of the sub-apertures remains a difficult task, dominated by the difficulty of phase measurements with optical quadratic detectors. The alignment procedure is held in two steps: a coarse phasing to correct strong instrumental perturbations (after a space deployment for example) followed by a fine phasing. The perturbations to correct in such systems are the relative orientation of sub-apertures (tip/tilt aberration) and the optical path differences between sub-apertures (piston aberration).

Focal-plane wavefront sensing is an elegant solution to measure the segment misalignments. Since the focal (and/or near focal) image(s) of any source taken by a 2D camera shows distortions when the system is not perfectly aligned, the system misalignments can be retrieved by solving the inverse non-linear problem. The main interests of this technique are that this wavefront sensor is included in the main imaging detector, simplifying the hardware and does not introduce a differential path between wavefront sensor and science camera. In addition, the focal image intrinsically contains information resulting from the interferometric (or not) superposition of all the sub-aperture beams, allowing measurements even on discontinuous sub-apertures. The phase retrieval technique, based on the sole focal-plane image, is generally not sufficient to solve for all ambiguities. The phase diversity technique, typically based on a focal and a slightly defocused image, removes all ambiguities and operates even on unknown extended sources.

We show here that a phase-diversity sensor can fully and efficiently align a multiple-aperture system, both for the coarse and fine phasing modes, with low computing cost algorithms. We describe the required algorithms, quantify their performance by numerical simulations and experimentally demonstrate their capability.

For the coarse phasing mode, we introduce ELASTIC (Estimation of Large Amplitude Subaperture Tip-tilt from Image Close-by data), a new series of algorithms enabling for the first time (to the best of our knowledge) a full-field tip/tilt non-iterative estimation from only a pair of diversity images and a simple on-the-fly data-processing. All the segments can be co-aligned after two successive closed-loop sequences. First, an ELASTIC variant based on exact wide-field tip/tilt estimation puts the focal spots in a reference position, and then a second variant based on a local linearization is used to superimpose the spots. The correction of large-amplitude piston can be then performed with classical techniques such as channelled spectrum or 1D scan. An additional advantage of the ELASTIC algorithm is to maintain tip/tilt control while the pistons are changed.

For the fine phasing mode, several versions of fast phase diversity for piston/tip/tilt measurements are currently investigated and compared [Mocoeur et al. Optics Letter (2009) and Denolle et al. Proc. SPIE 8713 (2013)].

The experimental validation of these algorithms is performed on a dedicated testbed at ONERA, including an unresolved source, a segmented mirror with 19 piston/tip/tilt active segments, and a phase diversity sensor.

The experimental and numerical results we will present quantify the performances of this novel, automatic and fast way to align the segments of a multi-aperture system.

9906-97, Session PS2

OVMS-plus at the LBT: disturbance compensation simplified

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The optical vibration measurement system (OVMS) at the LBT [1] was commissioned in 2013 and since then accelerometer values are continuously measured and archived at all 6 mirrors of the telescope. The values are digitized and distributed via multicast to various clients. However, the original design left the calculation of OPD, TIP and TILT disturbance values to each instrument's control loop. In hindsight, this does not seem reasonable. To increase synergy between using and testing OVMS with different instruments, we now implemented a centralized calculation of OPD, tip and tilt, as these calculations do not rely on instrument specific parameters. We use a broadband filter published in [2] to estimate the OPD and the TIP and TILT values for each mirror. With these values, instrument specific gains and coordinate transformations can now be used to transform the tip and tilt into focal plane centroid shifts. These shifts, together with accelerometer values, are then distributed via multicast.

Additionally, we use a delay compensation algorithm to compensate for the measurement delay of 3ms and for potential additional delay occurring in the compensation loops of the instruments. The respective algorithm is based on an extension of the original broadband filter and will be sketched in the paper, but is described in more detail in a publication currently under review.

The new architecture simplifies the use of the OVMS for the users and makes the mirror motions easily available for anyone. This greatly enhances the functionality of the OVMS and enables instrument engineers and scientists to focus on other challenges they are facing with their instruments. At the same time they can rely on a quality estimate of the disturbance which can be used for feedforward disturbance compensation in the respective instruments.

Eventually, OVMS-plus will be an observatory facility provided and maintained by LBTO. LBTI is now the first user of the OVMS-plus and we will present on sky measurements illustrating the performance of the new disturbance estimation and compensation.

9906-98, Session PS2

Introduction to the SKA low correlator and beam-former system

Grant A. Hampson, John D. Bunton, Commonwealth Scientific and Industrial Research Organisation (Australia); Andre Gunst, ASTRON (Netherlands); Peter Baillie, Auckland Univ. of Technology (New Zealand)

The SKA organisation is building a low frequency (50-350?MHz) aperture array to be located in remote Western Australia. The array consists of 512-stations, each consisting of 256-dual polarisation log-periodic antennas. The stations are distributed over a distance 80?km, with the greatest density of stations located in the central core. The input bandwidth is processed in a two stage polyphase filterbank, with the first stage channeliser producing 384 x 781?kHz narrow band channels. Each station beamforms the antennas together to form a single dual polarisation beam with a bandwidth 300?MHz (additional beams can also be traded for bandwidth.) The second stage polyphase filterbank is located in a system called the Correlator and BeamFormer (CBF) [1] which is the topic of this paper.

The CBF processes the 512-stations to produce visibilities for imaging, as well as two pulsar outputs; search and timing. The CBF is capable of dividing the 512-stations into 16 independent subarrays - each with independent frequency resolution, integration time, and beams (with the caveat that each station only belongs to one subarray.) The CBF system requires 30?Tera-bits-per-second of data communications (inputs, cross-connects, outputs) combined with approximately 1?Peta-multiply-accumulates-per-second. The CBF system uses power efficient FPGAs to handle to the very high communication and processing rates. All FPGAs are optically connected to allow for arbitrary interconnections [2, 3]. Each FPGA, optical transceivers and memories are liquid cooled for higher efficiency and reliability.

The signal processing is divided into two types of processing; one at the station level and the other on the array of stations. The station based processing involves a second stage critically sampled filterbank which provides the necessary spectral line zoom modes going down to a frequency resolution of 226?Hz. There are also two other filterbanks for the pulsar processing; the pulsar search filterbank is also critically sampled at approximately 16?kHz, however the pulsar timing filterbank is oversampled so that after the narrowband beamforming it can be re-synthesised back to the original frequency resolution of 781?kHz. The station based processing also includes a delay correction (divided into coarse and fine adjustments) as well as RFI detection and excision.

The array based processing contains two core functions - correlation to generate visibilities and tied array beamforming for pulsar search and timing. A majority of the computations are contained in these two functions. The correlator always forms visibilities on 226?Hz channels and through post integration of frequency channels can form wider bandwidth channels, with the standard mode being 64k channels each of 4.5kHz. The beamformer processing is more than the standard multiply accumulate algorithm; for pulsar timing accurate off boresight beams require polarisation correction before beamforming for each look direction. However for pulsar search this is more relaxed and post beamforming polarisation correction is allowed. RFI excised station data is ignored in the correlator and beamformers.

In this paper the CBF system will be described on several different levels; from Matlab models to signal processing firmware, from FPGA to packaging/cooling, from the firmware framework to the peripheral interface firmware, and finally from the monitor and control software to how the CBF fits into the larger SKA Low instrument.

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9906-99, Session PS2

Large aperture millimeter/submillimeter telescope: which is more cost-effective, aperture synthesis telescope versus large single dish telescope?

Satoru Iguchi, Masao Saito, National Astronomical Observatory of Japan (Japan)

The Atacama Large Millimeter/submillimeter Array (ALMA) was built in a global partnership of ESO, NSF and NINS, and has been operated at an altitude of about 5000m for 5 years. The array consists of 66 antennas with high surface accuracy and high pointing accuracy with an operating wavelength range of 0.3 to 3 mm, which will be extended up to 8.5 mm in the future. For realizing high fidelity of imaging with mosaicing observations, the ALMA is designed to combine a homogeneous array of 50 12 m antennas (12 m Array) and the Morita Array - Atacama Compact Array (ACA) (4 12-m antenna and 12 7-m antennas) in order to cover all spatial frequency Fourier components of the brightness distribution of observed sources. The ALMA successfully realized a huge millimeter/submillimeter aperture equivalent to a 91-m diameter antenna.

The Green Bank Telescope (GBT) was built in 2000 and is the world’s largest, fully-steerable telescope with a diameter of 100 m in the wavelength range of 3 mm to 30 cm. The Large Millimeter Telescope (LMT) was built in 2011 and started early science operations as a 32-m diameter telescope in 2013 in the wavelength range of 1.3 to 4 mm. After the surface of the telescope is completed and adjusted, the LMT will be the world´s largest, steerable millimeter-wavelength telescope with a diameter of 50 m in the wavelength range of 0.85 to 4 mm. The Cerro Chajnantor Atacama Telescope (CCAT) is a proposed 25-m diameter telescope and will be the world’s largest, submillimeter-wavelength telescope.

The Aperture Synthesis Telescope can achieve a huge aperture with more than 100-m diameter with the advent of JVLA, ALMA and SKA, but it still has some scientific weak points due to technological limitations: for instance, small “field of view.” On the other hand, while the Single-dish Telescope can achieve a wide “field of view” with a multi-pixel radio camera and a multi-beam heterodyne receiver, it also has a disadvantage of requiring a huge aperture to achieve high sensitivities, due to several technological limitations.

We aim to identify what technological development items need to be addressed from scientific requirements based on several science use cases (e.g. wider field of view, higher sensitivity, higher angular resolution and wider bandwidth), by investigating advantages and disadvantages of both the Aperture Synthesis Telescope and the Large Single-dish Telescope, including comparative analysis of their cost effectiveness. These study results will be presented as a proposal of the design of antenna structure for a future telescope project at millimeter and submillimeter wavelengths.

9906-100, Session PS2

New co-phasing and AO strategies for an extremely large telescope dedicated to extremely high contrast: the Colossus project

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Detecting an exoplanetary life signal is extremely challenging with current technology because it requires a sensitive telescope and instrument that can measure the planet's reflected optical and infrared light, while distinguishing this from the star's scattered light and the terrestrial thermal noise background. This requires highly accurate adaptive optics, a coronagraph system, and a specially designed and aligned giant telescope. We present here new strategies for building such a telescope with large circular segments using adaptive optics correction independently for each of these segments prior to cophasing the segments. The foreseen cophasing technique uses focal plane images that allow piston measurements and correction between all the segments. In this context we propose to derive the segment phase error using the inverse approach knowing the segment positions and the single aperture Airy function. Preliminaries AO simulations and on-bench cophasing results are presented here.

9906-101, Session PS2

SPEED: The Segmented Pupil Experiment for Exoplanet Detection: design advances and progress overview

Patrice Martinez, Observatoire de la Côte d'Azur (France); Olivier Preis, Carole Gouvret, Lab. J.L. Lagrange (France); Julien Dejonghe, Observatoire de la Côte d'Azur (France); Mathilde Beaulieu, Pierre Janin-Potiron, Lab. J.L. Lagrange (France); Alain Spang, Observatoire de la Côte d'Azur (France); Lyu Abe, Lab. J.L. Lagrange (France); Frantz Martinache, Observatoire de la Côte d'Azur (France); Yan Fantéï-Caujolle, Lab. J.L. Lagrange (France); Aurélie Marcotto, Marcel Carbillet, Observatoire de la Côte d'Azur (France)

Direct imaging of exoplanets ideally down to Earth-like planet is one of the most exciting but challenging area in modern astronomy. In this context, segmented telescopes appears as the next leap forward for both ground- and space-based observatories for increasing significantly the exoplanet detection paradigm.

However, along with the unavoidable run for spatial resolution and photon sensitivity comes a catch that leads to telescope architectures that by design are far from optimal for the exoplanet search problem.

Inevitably, various problems and brand new critical issues such as pupil discontinuities, missing segments, stellar resolution, Fresnel effects, etc., make high-contrast imaging more demanding with the next generation of observatories (E-ELT, TMT, AFTA-WFIRST, LUVOIR, etc.).

The SPEED testbed is designed to enable a wide range of studies of these asymmetric and unfriendly apertures related issues. The upmost objectives of the SPEED bench are (1) to develop in-depth expertise in instrumental design and control of contrast considering Fresnel/Talbot effects; (2) to improve high-contrast imaging observing mode toward very small inner-working angle; (3) to develop new co-phasing sensors at the telescope or at the instrument level to serve as a primary co-phasing sensor or for a fine-tuning and/or temporal stability control purposes.

This communication reports on the progress in the development of the SPEED facility. We describe the testbed optical and opto-mechanical design performance. More specifically, we discuss as-build optics surface errors, multi-deformable mirrors architecture regarding Fresnel effects, coronagraph design, and advance in the development of a new co-phasing sensor. Finally, first light results are presented.

9906-102, Session PS2

Improving E-ELT M1 prototype hard position actuators with active damping

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During the advanced design phase of the European Extremely Large Telescope (E-ELT) several critical components have been prototyped. In particular, a representative section of the E-ELT primary mirror has been assembled. It is equipped with complete prototype segment subunits including prototype edge sensors and position actuators. One purpose is to test various control strategies and evaluate the achievable performance. One of the segment subunits is equipped with three prototype 'hard' actuators, i.e. typically piezo actuators being passively stiff. To improve such type of position actuators various active damping techniques were implemented and tested. In this paper an active damping strategy based on positive position feedback is introduced. The theoretical and implementation test results are presented. This also includes results related to vibration transmission.

9906-103, Session PS2

SPEED (Segmented Pupil Experiment for Exoplanet Detection) design optimization via Fresnel propagation analysis

Mathilde Beaulieu, Lyu Abe, Patrice Martinez, Carole Gouvret, Farrokh Vakili, Lab. J.L. Lagrange (France)

Future extremely large telescope will open a unique niche in the detection and characterization of faint exoplanet close to their sun. However this kind of large telescope requires segmented primary mirror (~ 800 segments to achieve diameters of ~ 40 m) that creates gaps between each mirror segments. Those discontinuities, combined with the secondary mirror obstruction and spiders are a major concern for high-contrast imaging that future instrument will have to deal with. A promising technique is the wavefront shaping which consists in the combination of a coronagraph and two deformable mirrors (DM). Located in non-conjugated planes, these mirrors can correct for both phase and amplitude aberrations, and be controlled to create dark zones at the focal plane. Algorithm and laboratory demonstrations have been made since in the past 20 years, but mainly in the continuous surface case.

SPEED (Segmented Pupil Experiment for Exoplanet Detection) is an experiment, started at Lagrange laboratory, Observatoire de la Cote D'Azur, in early 2013 to test high contrast capabilities with segmented pupils at very small separations (~ 1 ?/D) in H-band. The science driver for this project is the observation of planets around M-star. SPEED will combine a coronagraph and adaptive optics (2 deformable mirrors) to create high contrast regions (dark holes) at small separation. The SPEED coronagraph will be a PIAACMC (Phase Induced Amplitude Apodization Complex Mask Coronagraph) combining two out-of-pupil apodized optics and a complex focal mask that provide very high contrast at very small separation (1 ?/D or less). We have developed simulation tools to study the achievable

contrast with “unfriendly” pupils, but also to optimize the optical layout (optics locations, sizes…). An end-to-end simulation has been developed that includes the Fresnel propagation between each SPEED optic.
This paper presents updated results of these simulations for the setup optimization part. The DM optimum location is a key point for the layout optimization. We study the best solutions in different configurations: in collimated beams (when the first DM is at the pupil plane and the second DM is out of the pupil plane and when the two DMs are out of pupil plane), and in converging beam (first DM at pupil plane, second DM in converging beam). The simulations are currently done with perfect coronagraph and ideal DMs in order to study the mirror distance impact and assess the ultimate effects of Fresnel propagation on contrast performances. We show that the best contrast performance, whether the first DM is located out of the pupil plane or not, is always achieved for a constant separation (rather large in our case) between the two DMs, the latter being only determined by the dark zone parameters.

9906-105, Session PS2

Segment handling system prototype progress for Thirty Meter Telescope

Satoru Sofuku, Yutaka Ezaki, Noboru Kawaguchi, Toshitaka Nakaoji, Yusuke Saruta, Masaki Haruna, Lyon Kim, Mitsubishi Electric Corp. (Japan)

SHS (Segment Handling System) is the subsystem permanently implemented on TMT’s telescope structure that enables fast, efficient, semi-automatic exchange of M1 segments. TMT plans challenging segment exchange (10 segments per 10 hours a day). To achieve these, MELCO develops innovative SHS by accommodating FA (Factory Automation) technology such as force control system and machine vision system into the system. Force control system used for install operation, achieves soft handling by detecting force exerted to mirror segment and automatically compensating the position error between handling segments and primary mirror. Machine vision system used for removal operation, achieves semi-automatic positioning between SHS and mirror segments to be handled. Prototype experience proves soft (extraneous force ~100N) and fast (~3 minutes) segment handling. The SHS will provide upcoming segmented large telescopes for cost-efficient, effortless, and safe segment exchange operation.

9906-106, Session PS2

Force control technology of segment mirror exchange robot for Thirty Meter Telescope

Masaki Haruna, Lyon Kim, Kazuhiko Fukushima, Satoru Sofuku, Toshitaka Nakaoji, Junji Takaki, Yusuke Saruta, Noboru Kawaguchi, Yasushi Horiuchi, Yutaka Ezaki, Mitsubishi Electric Corp. (Japan)

SHS (Segment Handling System) is the subsystem permanently implemented (installed to) on TMT’s (telescope) structure that enables fast, efficient, semi-automatic exchange of M1 segments. TMT plans challenging segment exchange (10 segments per 10 hours a day). To achieve these, MELCO develops innovative SHS by accommodating FA (Factory Automation) technology such as force control system and machine vision system into the system.

Our developed force control technology makes it possible for SLF (Segment Handling and Fixture) to achieve safe and reliable mirror segment exchange of which mechanical interfaces are designed under the back side of the segment where machine vision system hardly measure the relative position. Owing to both well-studied design of the interface between the mirror segment/the jack of the telescope and the force control algorithm, the difficulty of the decoupling between the translational and rotational forces could be solved and enabled SLF to exchange the segment with acceptable performance. The effectiveness of our developed technology was verified through the experiments using the almost full scale prototype SLF that segment exchange could be completed within 180sec which was required from the system budget of SHS under all the assumed situations which included various relative position and attitude errors between SLF and the segments, and inclination of the segment from 0deg to 14.5deg.

This presentation focused on the concrete technology of SLF force control would contribute to deeper understanding of the MELCO’s SHS.

9906-107, Session PS2

Accelerometer-based online reconstruction of fast telescope vibrations from delayed measurements

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The imaging quality of ground-based telescopes is largely affected by telescope vibrations induced by wind, ground-vibrations or vibrations of technical equipment on site. A feedforward vibration cancellation system can be used to cancel fast wind-induced telescope vibrations out of the optical imaging system. This feedforward loop unburdens the adaptive optical system of the telescope. The disturbance feedforward system is based on accelerometer-measurements of the telescope vibrations, a position reconstruction algorithm to reconstruct the vibrational displacement based on the measured acceleration and a piezo-driven compensation mirror used to cancel the vibrations out of the optical path. Crucial is the position reconstructor’s ability to provide the compensation mirror with an accurate online estimate of the vibrational displacement. In this case, the vibrational disturbances will be canceled entirely. The authors have developed and presented a sophisticated position reconstruction algorithm based on adaptive resonators. Ultimately, the proposed disturbance feedforward control system permits observing faint stars with sufficient imaging contrasts on both the wavefront sensor and the main observational camera while disturbances caused by mechanical vibrations of the telescope structure are compensated for by a disturbance feedforward system.

Network data transmission protocols like UDP are typically used to transmit the acceleration measurement signals from the sensors to the control system computer. This data transmission introduces a non-negligible time delay into the measurement chain. However, any effective feedforward compensation setup can only function well if a delay-free estimate of the disturbance signal is provided. The consequences of a measurement time delay for vibrational feedforward compensation systems are discussed and illustrated. Three delay-compensating extensions of the developed position reconstructor are presented and analyzed. These modified position reconstructors have the same advantageous properties as original the adaptive resonator reconstructor, for example strong attenuation of both low-frequency drift and high-frequency noise. In addition, the measurement delay is compensated for in a predictive way. The reconstructed position signal is thus free of delay and can be used for disturbance feedforward compensation.

9906-108, Session PS2

The Square Kilometre Array mid-digital receiver concept

Gie Han Tan, SKA Organisation (United Kingdom) and European Southern Observatory (Germany); Krzysztof

Caputa, NRC - Herzberg Astronomy & Astrophysics (Canada); Stéphane Gauffre, Ctr. de Recherche Paul-Pascal (France); Thushara K. Gunaratne, Zoran Ljusic, NRC - Herzberg Astronomy & Astrophysics (Canada); Adriaan Peens-Hough, SKA South Africa (South Africa); Benjamin Quertier, Ctr. de Recherche Paul-Pascal (France)

The Square Kilometre Array (SKA) project is a global science and engineering project aiming at designing and constructing the next-generation radio telescope operating in the metre and centimetre wavelengths regions. The first phase of construction of the telescope (SKA1), which represents roughly 10% of the full SKA (SKA2), is currently well advanced with its design and expected to be operational early next decade. The SKA radio telescopes will be co-hosted in two locations with central array sites in Australia, SKA1-Low (50 – 350 MHz), and South Africa, SKA1-Mid (350 MHz – 13.8 GHz with an option for > 20 GHz).

This paper will address the use of state-of-the-art analogue-to-digital converters (ADC) and subsequent digital signal processing in the broadband receivers deployed in the SKA1-Mid radio telescope. The most recent developments in ADC technology has resulted in the availability of very fast and high resolution converters that are ideally suited for the SKA1-Mid telescope and enable direct digitization, after ample amplification by very low noise amplifiers, at RF signal frequencies as high as 13.8 GHz.

This novel concept for radio telescopes avoids the need for frequency conversion in the analogue front end. Except for broadband, anti-aliasing, filtering in the RF chain all bandpass filtering and frequency conversion will be performed in the digital domain. This direct digitization concept avoids the need for local oscillator signals, introducing the risk of unwanted spurs, and gives increased flexibility in catering the different back-ends dedicated to different types of astronomical science.

SKA1_Mid foresees in a total of five receiver bands, Band 1 (350 – 1050 MHz), Band 2 (950 – 1760 MHz), Band 3 (1650 – 3050 MHz), Band 4 (2800 – 5180 MHz) and Band 5 (4.6 – 13.8 GHz). For each of these bands the digitizers have to cope with different RF scenarios and appropriate ADC resolution and sampling frequencies are selected.

After digitization of the RF band various steps of signal processing, including digital down-conversion and filtering, are performed at the antenna before central correlation or beam-forming.

9906-109, Session PS2

Blind and reference channel-based time interleaved ADC calibration schemes: a comparison

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Time-interleaved (TI) ADCs are used to improve the sampling frequency of the ADCs by operating more than one in parallel. Time-interleaving, however, produces nonlinear terms due to the aliasing of the signals, and these distortion terms can only be eliminated if all the channels have the same offset and frequency response (gain, timing and bandwidth). All mismatches produce distortions, even if they are linear in nature, like these.

Blind calibration techniques exploit the properties of the input signal, or of time-interleaved systems, to estimate the calibration parameters required to maximize linearity. For instance, if the signal is from DC to a certain fraction of the Nyquist band, it is shown that aliasing in a 2-channel TI-ADC will create around the Nyquist frequency. Other techniques exploit the property that the signal and its derivative are orthogonal (bandwidth and timing errors can be approximated as a derivative).

Reference-based techniques, on the other hand, use a reference channel to obtain a reference signal: they exploit the property that if all the channels have the same offset and frequency response, no aliasing occurs. Calibration forces the offsets and frequency responses of all the channels to be the same as the reference channel, thus eliminating aliasing.

For a number of channels higher than 4, an additional reference channel implies a small overhead cost to the system, requires a thorough redesign of the whole system, and cannot be applied to OTS TI-ADCs. For 2 and to a lesser extent 4 channels, however, the overhead is large and blind calibration techniques may be preferred.

This paper compares both types of techniques for 2- and 4- channel TI-ADCs in terms of accuracy and convergence speed. Convergence speed is important because time-varying errors can be more easily tracked with a fast algorithm, which achieves thus a higher linearity during the tracking. Computational complexity is also considered, using the both LMS and RLS versions of the adaptive filters (which introduce a further trade-off between complexity, convergence speed, and steady-state linearity).

There are many blind and reference-based techniques in the literature, differing in terms of complexity, accuracy, speed. Comparison is performed among several of them, using the same testbed to assure the replicability of the results. The sources of mismatch investigated in this paper are offset, gain, timing and bandwidth.

9906-111, Session PS2

The Gemini Observatory protected silver coating: ten years in operation

Thomas Schneider, Gemini Observatory (United States); Tomislav Vucina Parga, Claudio Araya, Cristian Moreno, Gemini Observatory (Chile); Clayton Ah Hee, Gemini Observatory (United States)

Since 2004 the Gemini telescopes have used a protected 4-layer silver coating on their 8-meter diameter primary mirror and other smaller optics. Protected silver was chosen for the twin telescopes due to its high reflectivity and low emissivity properties. For over 10 years the protected 4-layer silver coating at Gemini has met the science requirements for reflectivity of 88% between 0.3-0.7 ?m and 84% between 0.7-1.1 ?m. Initial requirements also stipulated that the coating should last at least two years, which have been met and exceeded. All mirrors have at least met the durability requirement, with most outlasting it significantly. Provided is a ten year retrospective on the progress in the use and maintenance of 4-layer silver coatings on large astronomical optics.

9906-113, Session PS2

E-ELT project: more than 10 years of design, engineering and management preparation for the biggest telescope ever

Gianpietro Marchiori, Francesco Rampini, Simone De Lorenzi, Leonardo Ghedin, Stefano Mian, Cristiana Manfrin, Cristina Battistel, Enrico Marcuzzi, EIE Group s.r.l. (Italy)

The European Extremely Large Telescope by ESO (European Southern Observatory) is at present the most sophisticated technology challenge ever conceived before. For more than 10 years, upon specific contracts with ESO, EIE GROUP has developed research and analysis activities with the aim of finding all possible solutions to meet the over 1000 main requirements envisaged by the Dome and Telescope Main Structure. The technologies defined, will allow remarkable improvements for the

future extremely large Telescopes and Domes, as it happened with those adopted for the four VLTs. The hub of all processes is the innovative System Engineering Approach, which has allowed to combine together scientific, functional, operational, safety and maintenance parameters, though maintaining costs and lead time within the frame envisaged by these projects. Wind and seismic extreme parameters and the relevant rules, have imposed non-conventional solutions. All manufacturing and pre-assembly processes, the Packing and Transport ones, and Erection on site have been analyzed in detail and verified in order to guarantee the overall performances.

9906-114, Session PS2

Design and study of the mask exchange system based on Delta parallel mechanism

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Mask exchange system is the main part of Multi-Object Broadband Imaging Echellette (MOBIE) on the Thirty Meter Telescope (TMT). The robot is one of the key parts in the mask exchange process. In view of the facts that the scheme the on-board robot is hard to meet the requirements of TMT and the traditional industrial robot is difficult to use in the Mask Exchange System (MEX). The delta parallel mechanism has much advantages such as good dynamic performance, high speed and could integrate a vision recognition system to identify the masks. The design for MEX based on off-board Delta parallel mechanism was proposed in the paper.

The stiffness models of MEX based on Delta parallel mechanism with different structure parameters in SolidWorks were analyzed to obtain relationship between different parameters and stiffness. Workspace of different Delta robots were calculated in MATLAB to gain relationship between parameters and workspace. These provide guidance for the design of Delta parallel mechanism which could use in different MEX schemes. By the requirements of MOBIE and preliminary schemes, the parameters of Delta parallel mechanism were determined and 3D models was established. Then, the kinematics analysis of Delta robot model was carried out to obtain the relationship between the driving arm and the position of the center point of the moving platform. On this basis, the MEX model was imported into MOBIE model to study schemes and obtained the routings. MATLAB and ADAMS software were used to perform simulation analysis and optimize the route to acquire the kinematics parameters. According to research above, advantages and disadvantages of various schemes were analyzed and compared. Through these studies, the basis and guidance for Delta parallel mechanism were provided in the MEX system design. The whole research process shown in the paper provided a reference for this specific project.

9906-115, Session PS2

Concepts for testing starshades on the ground

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Starshades are external occulters that would be used in conjunction with a space telescope and are being considered for future missions which will search for and characterize nearby exoplanets. Testing starshade technology on the ground is not straightforward because of the spatial scales involved. To reach small inner working angles (IWAs) the physics of diffraction dictates starshade size, so that for an IWA of 100 mas for example, something like a 30 m class starshade is needed. The corresponding separation of starshade and telescope would be of order 40 Mm. Such scales are obviously impossible on the ground, but can anything be done to test our understanding of starshades without going into space, and can any useful astronomy be done with ground-based starshades? We discuss concepts for testing meter class starshades using modest aperture telescopes such as the 2.1 m McMath solar telescope and applying the technology to larger telescopes with an adaptive optics system such as the 8.1 m Gemini telescopes. Larger telescopes which will enable larger but still subscale starshades are nearing construction. Realizable starshade geometries employing fixed ground-based assets are considered. We review some possible astronomical targets and consider the effects of atmospheric seeing on contrast. Finally we consider whether such starshades can be used to test current models of diffraction for small deformations of the shade.

This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

9906-116, Session PS3

Design of the high precision thermostat for birefringent filter

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A high precision thermostat design was presented to improve the temperature stability of the birefringent filter for the solar telescope in Huairou Solar Observatory. As the first step, three types of temperature sensors were investigated, PT, NTC thermistor and Wheatstone bridge. To grab the small temperature variations from these sensors, a complicated weak signal detection circuits with a 24 bits AD was designed; Then, high efficiency thermal insulation layers and a peripheral constant temperature layer were designed and set up to minimum thermal exchange; Finally, an ARM 7 processor was used as the central processing unit and the intelligent PI heating algorithm was realized. Two sets of thermostats had been put into use for more than two years, the temperature stability is better than 0.01??

9906-117, Session PS3

The Single Mirror Small Size Telescope (SST-1M) of the Cherenkov Telescope Array

Enrico Junior Schioppa, CERN (Switzerland)

The Small Size Telescope with Single Mirror (SST-1M) is one of the proposed types of Small Size Telescopes (SST) for the Cherenkov Telescope Array (CTA). The CTA south array will be composed of about 100 telescopes, out of which about 70 are of SST class, which are optimized for the detection of gamma rays in the energy range from 3TeV to 300TeV.

The SST-1M implements a Davies-Cotton optics with a 4m dish diameter providing a field of view of 9 degrees. The Cherenkov light produced in atmospheric showers is focused onto a 88cm wide hexagonal camera, composed of 1296 custom designed large area hexagonal silicon photomultipliers and a fully digital readout and trigger system. The SST-1M camera has been designed to provide high performance in a robust as well as compact and lightweight design.

In this contribution, we review the different steps that led to the realization of the first telescope prototype and its innovative camera.

9906-118, Session PS3

Cryogenic performances of high-efficiency germanium immersion grating

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We present optical performances of a high-efficiency Germanium immersion grating under a cryogenic condition. Immersion grating is a diffraction grating of which the grooved surface is immersed in a medium with high refractive index (n). This optical device can offer n times higher spectral resolution than a classical reflective grating with the same clear aperture, thus it enables us to realize compact spectrographs keeping the spectral resolution. This new device will play important roles for infrared astronomy in the next generation.

We have been developing immersion gratings made of a variety of infrared crystals. Recently, we succeeded in fabricating a CdZnTe immersion grating with the theoretically predicted diffraction efficiency by machining process using an ultrahigh-precision five-axis processing machine developed by Canon Inc. (Ikeda et al. 2015). This achievement has a great impact because the direct cutting technique is applicable for any kind of infrared crystals, while the etching method, which was succeeded by a group of University of Texas, is used for fabricating a single crystal Si immersion grating.

Using the same technique, Canon Inc. completed a practical Ge-immersion grating with both a reflection coating on the grating surface and the an AR coating on the entrance surface. As an application, we are developing a long-NIR (2-5 um) high-resolution (R=80,000) spectrograph, VINROUGE, which will be the first IR spectrograph with a Ge-immersion grating. Thanks to the high refractive index of Ge, the instrument size is very compact (600 mm x 600 mm x 500 mm) for the spectral resolution (see Arasaki et al. in this conference). The Ge-immersion grating has a blaze angle of 75 degree and a diffraction surface area of 104 mm x 31 mm. Although the high optical performance is confirmed at room temperature (diffraction efficiency > 70%), it is necessary to verify it under the cryogenic condition. We built an in-house equipment to measure the light diffracted by the immersion grating at 4-4.5 um under variable cryogenic condition (20-80 K). This system employs a quantum cascade tunable laser in a single mode with a band width of < 6.8e-6 um, as the light source. The spatially-cleaned and expanded collimated beam enters and diffracted back by the immersion grating in the perfect Littrow configuration, being focused on a two-dimensional PbSe detector. TE or TM modes can be selected by a rotating half-wave plate. Both the immersion grating and a reference mirror are mechanically switchable under the cryogenic condition without changing the light path. We report the diffraction efficiency determined by using the system and robustnesses of the coatings on the Ge-immersion grating against thermal cycles.

9906-119, Session PS3

Optical designs for the Maunakea Spectroscopic Explorer Telescope

Will Saunders, Peter R. Gillingham, Australian Astronomical Observatory (Australia)

We present two optical designs for the proposed Maunakea Spectroscopic Explorer (MSE) telescope. The AOmega is twice as large as for existing wide-field spectroscopic designs (DESI, PFS), and the desired wavelength range is also larger (0.36-1.8 microns). The wide field corrector (WFC) for both designs includes a Compensating Lateral ADC which allows atmospheric dispersion correction without additional elements. A 12.3m F/2.97 Cassegrain design derived from VISTA gives 1.4 degree field-of-view with just three silica lenses. The largest lens is spherical with aperture diameter 1.26m, the other two are ~1.1m with a concave asphere. This design is pupil-centric, unvignetted and remarkably compact. An 11m F/1.97 Prime Focus design with 1.52 degree field is also presented. The WFC consists of five elements, three large and strongly powered silica lenses, and two thin and weakly powered light flint elements. The largest element is 1.21m aperture diameter, all other elements are <1m. All lenses have a concave asphere, one very strong but a pure conic. Blanks are available for all lenses. The ADC action involves moving the hexapod and just one individual lens, and a simple and robust single-actuator mechanism for this is also presented. The ADC action also allows a small change in plate-scale, which halves the image motions caused by differential refraction. A modest amount of vignetting at L1 allows the design to be effectively pupil-centric. Both designs give d80 < 0.35”-0.45” depending on zenith distance. The prime focus design has been adopted by MSE as the baseline design.

9906-120, Session PS3

SALT segmented primary mirror: experience with alignment control with inductive edge sensors

Hitesh Gajjar, John W. Menzies, Chris Coetzee, Ockert Strydom, Jonathan Love, Keith R. J. Browne, South African Astronomical Observatory (South Africa)

The Southern African Large Telescope (SALT) is a 10-m class 91-segment fixed altitude telescope located at Sutherland, South Africa. The segment alignment is maintained by inductively coupled sensors mounted on Sitall brackets beneath the segments. An extensive period of testing in environmental chambers and on the telescope has been conducted to establish the stability of the sensors and their response to temperature and humidity variations in the telescope chamber. We present some of the test results, including a demonstration of the ability of the sensors to maintain the alignment of a subset of the array over a period of 20 days.

We also present the initial results following the commissioning of the full edge sensing system on the telescope, technical challenges and lessons learned.

9906-121, Session PS4

Liverpool Telescope 2

Chris M. Copperwheat, Iain A. Steele, Robert M. Barnsley, Stuart D. Bates, Michael F. Bode, Neil R. Clay, Chris A. Collins, Liverpool John Moores Univ. (United Kingdom); Johan H. Knapen, Instituto de Astrofísica de Canarias (Spain); Jonathan M. Marchant, Christopher J. Mottram, Robert J. Smith, Liverpool John Moores Univ. (United Kingdom)

In this talk we will provide a progress report on Liverpool Telescope 2 (LT2): a new, fully robotic optical/infrared telescope planned to be commissioned at the Observatorio del Roque de los Muchachos (ORM) on the Canary island of La Palma in the early years of the next decade. Robotic telescopes are powerful tools for the study of the time variable sky. The 2-metre Liverpool Telescope, sited at the ORM, is one of the world’s leading time domain facilities, and LT2 will build on the success of this telescope with a larger aperture, novel instrument complement and an even more rapid response time for highly variable and fast-fading

transients. It is an exciting period for time domain astronomy: we are on the brink of a new era which will brought about by the next generation of discovery facilities such as LSST, SKA, SVOM and CTA. These facilities will survey vast regions of the sky and detect unprecedented numbers of transients and time variable phenomena across the electromagnetic spectrum. Facilities like Advanced LIGO / Virgo and IceCube will are also beginning to open non-electromagnetic windows on the transient universe for the first time. A key problem is a lack of follow-up facilities for classification and exploitation of these new discoveries. LT2 is designed to meet this need: a modern, large aperture and reactive robotic telescope to maximally exploit the discovery space of the new time domain era.

9906-122, Session PS4

LSST AOS software architecture

Sandrine J. Thomas, Srinivasan Chandrasekharan, Paul J. Lotz, Bo Xin, Charles F. Claver, George Z. Angeli, Jacques Sebag, LSST (United States); Gregory P. Dubois-Felsmann, California Institute of Technology (United States)

The Large Synoptic Survey Telescope (LSST) is an 8-meter class wide-field telescope now in construction on Cerro Pachon, Chile. This ground-based telescope is designed to conduct a decade-long time domain survey of the optical sky. In order to achieve the LSST scientific goals, the telescope requires delivering a robust good image quality over the 3.5 degrees field of view. As many telescopes, LSST will use an Active Optics System (AOS) to correct in real time the system aberrations mostly introduced by gravity and temperature gradients. The LSST AOS uses a combination of 4 curvature wavefront sensors (CWS) located on the outside of the LSST field of view. The information coming from the 4 CWSs are combined to calculate the appropriate corrections to be sent to the 3 different mirrors. The AOS software is composed of a wavefront sensor estimation pipeline (WEP) and an active optics control system (AOCS). The WEP estimates the wavefront residual error from the CWS images. The AOCS determines the correction to be sent both the M1/M3 and M2 mirrors every 30 seconds. In this paper, we describe the design and implementation of the AOS. More particularly, we will focus on the software architecture as well as the AOS interaction with the different subsystems within LSST.

9906-123, Session PS4

A new telescope design suitable for massive spectroscopy

Luca Pasquini, Bernard-Alexis Delabre, Tim de Zeeuw, European Southern Observatory (Germany)

In the framework of a thought experiment, we present a novel concept for a five- mirror telescope design, especially suitable for massively multiplexed spectroscopy. The concept provides a large field of view (FOV) in a convenient, gravity-invariant focal plane that can be adapted to a large range of telescope diameters. As a specific example we present a design for an 8m diameter telescope with a 1.5 degree diameter FOV and a relay system that allows simultaneous spectroscopy with 10000 mini-integral field units over a square degree, or, alternatively a 5x4 arc-minutes giant integral-field-unit, by using 240 MUSE-type spectrographs. The importance is stressed of simultaneously developing telescope and instrument.

9906-124, Session PS4

ASTRI camera electronics

Giuseppe Sottile, Osvaldo Catalano, Giovanni La Rosa, Milvia Capalbi, INAF - Istituto di Astrofisica e Planetologia Spaziali (Italy); Carmelo Gargano, Salvatore Giarrusso, Domenico Impiombato, INAF - Istituto di Astrofisica e Planetologia Spaziali (Italy); Francesco Russo, Pierluca Sangiorgi, Alberto Segreto, INAF - Istituto di Astrofisica e Planetologia Spaziali (Italy); Giovanni Bonanno, Salvatore Garozzo, Davide Marano, Giuseppe Romeo, INAF - Osservatorio Astrofisico di Catania (Italy); Luca Stringhetti, INAF - IASF Milano (Italy); Renato Gimenes, Univ. de São Paulo (Brazil)

ASTRI SST-2M is a Cherenkov Telescope prototype developed by INAF and proposed as one of the Small Size Telescope (SST) options for the Cherenkov Telescope Array (CTA) observatory. It is based on a dual mirror optic system, an innovative solution for Cherenkov light imaging. The focal plane of the ASTRI camera is composed of silicon photo-multipliers (SiPMs), a recently developed technology for light detection that exhibits very fast response and an excellent single photoelectron resolution. The ASTRI camera electronics is specifically designed to catch the fast pulses produced by the SiPM sensors.

To optimize the overall camera design, the ASTRI Camera Electronics is divided into two main systems: the Front End Electronics (FEE) and the Back End Electronics (BEE).

Each one of the 37 photon detection modules (PDMs), constituting the camera focal plane, hosts its own FEE. In each PDM, the FEE is composed of a front end readout ASIC directly interfaced to the SiPM sensors, an ADC to convert the event pulses and a FPGA that implements all the required logic for the generation of a local trigger and the transmission of the data produced to the BEE.

The BEE is hosted on a separate common board. The BEE is based on a FPGA with a System on Chip (SoC) running an operating system that manages the configuration of all the 37 PDMs. The BEE receives commands from a camera controller and sends data packets to a camera server, both connected through a LAN.

In this contribution we present the general architecture of the ASTRI camera electronics with special emphasis to some innovative solution.

9906-126, Session PS4

LSST primary/tertiary monolithic mirror

Jacques Sebag, William J. Gressler, Ming Liang, Douglas Neill, Constanza Araujo Hauck, John Andrew, Chuck Gessner, Gary A. Poczulp, LSST (United States); Michael T. Tuell, Hubert M. Martin, Steve C. West, The Univ. of Arizona (United States); George Z. Angeli, Myung Kyu Cho, Bo Xin, LSST (United States)

At the core of the Large Synoptic Survey Telescope (LSST) three-mirror optical design is the primary/tertiary (M1M3) mirror that combines these two large mirrors onto one monolithic substrate. The M1M3 mirror was spin cast and polished at the Steward Observatory Mirror Lab at the University of Arizona (SOML). Final acceptance of the mirror occurred during the year 2015 and the mirror is now in storage while the mirror cell assembly is being fabricated. The M1M3 mirror will be tested at SOML after integration with its mirror cell before being shipped to Chile.

This paper details the results from the mirror final acceptance. All critical parameters were measured with sufficient accuracy to demonstrate compliance with the specifications. For each mirror M1 and M3, the vertex radius of curvature, conic constant, and position of the optical axis with respect to the mechanical axis of the blank were demonstrated to be within the specifications including the relative position of M3 optical axis relative to M1 optical axis. The residual surface errors for each mirror were also measured and analyzed by SOML and LSST to verify the impact on the final image quality of the telescope.

After final acceptance, the mirror surface was protected with a thin coating

of polyethylene to protect the mirror as it was prepared for removal of its polishing cell for delivery. Formal delivery happened toward the middle of May 2015 when the LSST Project took responsibility for the mirror in its shipping container and moved it to a secure facility for storage. The mirror is expected to remain in storage for approximately two years until the operational M1M3 mirror cell assembly is fabricated, at which time the M1M3 mirror and mirror cell can be integrated and tested before being shipped to Chile

9906-127, Session PS4

An afocal three-mirror optical system for 3D laser receiver and imaging detection

Xin Wang, Jinlong Wan, Shouwang Jiang, Rong Shu, Shanghai Institute of Technical Physics of the Chinese Academy of Sciences (China)

We present a novel 3D laser imaging optical receiver comprised by a coaxial three-reflective aspherical afocal telescope, an off-axis TMA camera and a lens laser collector, able to realize the altitude measurement and array spatial detection. The afocal design is to permit a very narrow filter to work at a high efficiency in the parallel ray beam and avoid the background spectral influence except for laser wavelength. Different from the coaxial R-C reflective plus lens corrector system, all reflective configuration shows very small distortion, more compact and easier to manufacture especially as larger and larger pupil size is in a great demand for the high spatial resolution. The distortion is optimized to be less than 5 micrometer in order to obtain the high image position. Several methods of measurement for interior orientation elements are studied, and the simulated analysis for measuring accuracy of principle point, principle focal length and distortion are achieved. The tolerance analysis for engineering application is done to give the detailed requirement on manufacture and alignment. An opto-mechanical stray light analysis is simulated to eliminate the straight ghost beams outside of FOV which graze the secondary mirror, then go across the inner hole of primary mirror, and finally arrive at the detector. A shutter with some laminas is designed which is connected with secondary mirror's structure, and the direct stray light is blocked completely. A lab prototype will be built in the next year.

9906-128, Session PS4

Effects of glycol on first surface aluminum coatings

David Sprayberry, Patrick Dunlop, Matthew Evatt, Larry Reddell, Ronald G. Probst, National Optical Astronomy Observatory (United States)

The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14000 sq deg will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs. The DESI Prime Focus Assembly will require liquid cooling to maintain its average temperature within ±1°C of ambient, so as not to disrupt the seeing. Because of concerns about fluid deposition onto optical surfaces from possible leaks in the cooling system, we are conducting systematic tests of the effects of candidate coolants on aluminized mirrors. Ethylene glycol is used extensively throughout the KPNO Mayall 4 meter facility, making it a good candidate coolant. Ethylene glycol is placed on test mirrors with first surface aluminum coatings for varying lengths of time. Various cleaning methods are then used to remove it. A spectrophotometer is used to analyze the condition of the coating before and after each experiment. The findings within this report reflect glycol as being a very volatile reactive solution when it comes in contact with first surface aluminum coatings. The effect seen is that of dissolving the aluminum coating. The results coincide with reports from other facilities that have experienced glycol leaks in cooling systems above first surface aluminum coatings.

9906-129, Session PS4

Optical design of the 25m CCAT sub-mm wave telescope

German Cortes-Medellin, Univ. de Antioquia (Colombia) and Cornell Univ. (United States); Stephen C. Parshley, Cornell Univ. (United States)

CCAT is a 25m-class sub-millimeter wave telescope designed to operate from 350-2100 microns (850-150 GHz), covering multiple telluric windows available at the unique site, 5612m above sea level, on Cerro Chajnantor overseeing the Atacama plateau in Northern Chile. CCAT will work in synergy with ALMA using a wide-field camera (among other instruments), opening the door for large scale survey missions to find targets that could be followed up with the very fine resolution of the ALMA array.

Affordability constraints created the need to slim down the very appealing but expensive 1˚ field of view in favor of a smaller FoV (1/3˚) but with the same scientific potential. Numerous optical designs were investigated that include an f/8 Nasmyth and quasi-Nasmyth as well as f/6 Gregorian designs. We will present the details of the final optical design including diffraction limited performance of these possibilities at the available focal locations, and the impact on scientific instrumentation.

9906-130, Session PS4

An all-silica three-element wide-field corrector design for GMT

Will Saunders, Peter R. Gillingham, Australian Astronomical Observatory (Australia); Sean Lin, Andrew P. Rakich, GMTO Corp. (United States)

We present a proposed design for a Wide-Field Corrector and Atmospheric Dispersion Compensator for GMT. It allows a 20' field of view with 3 fused silica lenses with diameter <1.55m, including just one low-precison asphere. For a 10' field, a smaller L3 without an aspheric surface suffices, giving somehat better monochromatic images than the uncorrected Gregorian focus as well as atmospheric dispersion correction. The polychromatic image quality is d80<0.05" at zenith and d80<0.20" for ZD<60 degrees, while the monochromatic image quality is d80<0.05" everywhere. The ADC action is achieved by tilt and translation of L1 and L2, via simple mechanisms each using a single encoded actuator. There is also a small motion of the M2 hexapod, automatically generated by the AGWS system. The design allows better UV and NIR throughput than can be achieved with the baseline Risley prism design, and blanks are known to be available in the required sizes and homogeneities. The main issues preventing the design being adopted at this time are that (a) the M2 motions are unbudgetted and it is not yet clear if they can be accommodated, and (b) the ADC action moves the exit pupil, which decreases throughput and allows off-axis stray light to enter the instruments. The exit pupil can be kept fixed by also translating and tilting L3, but this is complicated by space constraints and by L3 being below the instrument rotator. Mechanisms for achieving the required L3 motions are presented.

9906-131, Session PS4

Holographic telescope

Jefferson E. Odhner, Odhner Holographics (United States)

A telescope is designed, manufactured, and demonstrated that uses an achromatic configuration of diffractive optical elements. The color spread normally associated with holographic lenses is compensated for with a second sandwiched diffractive optical element that exactly cancels out the chromatic aberration of the first element. This technique is used to make the primary and objective optics. The advantage of this is that large aperture optics can be made that weigh significantly less than conventional optics. Various F/#'s were experimented with. The resulting lightweight telescope would be suitable for UAV (unmanned aerial vehicle) applications. The telescope was modeled in Zemax® (ray tracing software) and the modeled results are compared to experimental results.

9906-132, Session PS4

The design of an adaptive optics telescope: the case of DAG

Laurent Jolissaint, HEIG-VD (Switzerland); Onur Keskin, Isik Üniv. (Turkey); Sinan Kaan Yerli, Middle East Technical Univ. (Turkey); Cahity Yesilyaprak, Atatürk Üniv. (Turkey); Lorenzo Zago, HEIG-VD (Switzerland)

Turkey is taking a lift in astronomical science by preparing a new 4-m telescope for infrared observation at high angular resolution, with adaptive optics. First light is scheduled for 2019. The telescope image quality specification is set such that once the AO system is running, the telescope and other pseudo-static aberrations should be significantely smaller than the average residual optical turbulence. In other words, the observations must be limited by residual turbulence, not the telescope. Following this objective, we have systematically chosen, at each step, solutions that should offer the maximum stability of the AO instrumentation (only Nasmyth with no rotation of the instruments), the easiest access to the AO system (optical laboratory-like environement) and stringent requirements on the telescope active optics low order and high order wavefront residuals. This paper is a review of this design process.

9906-17, Session 6

Final design of the Large Synoptic Survey Telescope *(Invited Paper)*

Steven Kahn, SLAC National Accelerator Lab. (United States) and LSST (United States)

The Large Synoptic Survey Telescope (LSST) is a large-aperture, wide-field, ground-based telescope, designed to perform a time-domain imaging survey of the entire southern hemisphere of sky in six optical colors. The development and construction of LSST involves a public/private partnership with funding from the National Science Foundation, the Department of Energy Office of Science, and various private sources. Within the past two years, the Project team passed a series of final technical and management reviews conducted by both federal agencies, and is now fully approved for construction. The expected science performance of the final design remains consistent with the advertised performance that led to the New Worlds New Horizons decadal survey endorsement of LSST as the top-ranked new large facility in ground-based astronomy. The optical design incorporates 3-mirror wide field optical system; an 8.4 meter primary, 3.4 meter secondary, and 5 meter tertiary mirror that feed three refractive elements and a 64 cm 3.2 gigapixel focal plane camera. The data management system is designed to reduce, transport, alert, and archive the 15 terabytes of data produced nightly, and will serve raw and catalog data accumulating at an average of 7 petabytes per year. Additional access portals and tools developed with the LSST will extend the scientific reach of the survey to education and public outreach efforts of students and other non-professionals. LSST has completed key performance demonstrations and procurements for many critical systems including the telescope mount assembly, the summit facility, the dome assembly, the imaging sensors, the secondary mirror optical fabrication, the camera refractive optics, and the camera and secondary mirror hexapod system. Software data challenges and data releases designed to test software and algorithms to significant pre-construction levels have continued and have supported harvesting existing data sets for additional science. Construction on the summit is well-underway, and fabrication of all of the major subsytems is in process, leading to LSST "first light" in 2020, and the onset of the ten-year survey in 2022.

9906-18, Session 6

Final design of the LSST hexapods and rotator

Douglas Neill, LSST (United States); Ryan C. Sneed, Scott Kidney, Moog CSA Engineering (United States); Constanza Araujo Hauck, William J. Gressler, Paul J. Lotz, Dave Mills, Jacques Sebag, LSST (United States); Thomas A. Sebring, Xoptx LLC (United States); Michael Warner, Oliver Wiecha, LSST (United States)

The Large Synoptic Survey Telescope (LSST) is a large (8.4 meter) wide-field (3.5 degree) survey telescope, which will be located on the Cerro Pachón summit in Chile. Both the Secondary Mirror (M2) Cell Assembly and Camera utilize hexapods to facilitate optical positioning relative to the Primary/Tertiary (M1M3) Mirror. A rotator resides between the Camera and its hexapod to facilitate tracking. The final design of the hexapods and rotator has been completed by Moog CSA, who are also providing the fabrication, integration and testing. Geometric considerations preclude the use of a conventional hexapod arrangement for the M2 Hexapod. To produce a more structural efficient configuration the camera hexapod and camera rotator will be produced as a single unit. The requirements of the M2 Hexapod and Camera Hexapod are very similar; consequently to facilitate maintainability both hexapods will utilize identical actuators. The open loop operation of the optical system requires very low hysteresis. This requires that the hexapod actuators use flexures rather than more traditional end joints. Operation of the LSST requires high natural frequencies, consequently, to reduce the mass relative to the stiffness, a unique THK rail and carriage system is utilized rather than the more traditional slew bearing. This system utilized two concentric tracks and 18 carriages. To ensure safe and reliable operation the hexapod and rotators will undergo extensive testing.

9906-19, Session 6

LSST telescope and site status

William J. Gressler, National Optical Astronomy Observatory (United States)

The Large Synoptic Survey Telescope (LSST) Project received its construction authorization from the National Science Foundation in August 2014. The Telescope and Site (T&S) group has made considerable progress towards completion in subsystems required to support the scope of the LSST science mission. The LSST goal is to conduct a wide, fast, deep survey via a 3-mirror wide field of view optical design, a 3.2-Gpixel camera, and an automated data processing system. The summit facility is currently under construction on Cerro Pachón in Chile, with major vendor subsystem deliveries and integration planned over the next several years.

This paper summarizes the status of the T&S group, tasked with design, analysis, and construction of the summit and base facilities and infrastructure necessary to control the survey, capture the light, and calibrate the data. All major telescope work package procurements have been awarded to vendors and are in varying stages of design and fabrication maturity and completion. The unique M1M3 primary/tertiary mirror polishing effort is completed and the mirror now resides in storage

waiting future testing. Significant progress has been achieved on all the major telescope subsystems including the summit facility, telescope mount assembly, dome, hexapod and rotator systems, coating plant, base facility, and the calibration telescope. In parallel, in-house efforts including the software needed to control the observatory such as the scheduler and the active optics control, have also seen substantial advancement. The progress and status of these subsystems and future LSST plans during this construction phase are presented.

9906-20, Session 6

LSST mirror system status: from design to fabrication and integration plan

Constanza Araujo Hauck, Jacques Sebag, Ming Liang, Douglas Neil, Sandrine J. Thomas, William J. Gressler, LSST (United States)

Currently in Construction phase since 2014, the Large Synoptic Survey Telescope (LSST) is a large (8.4 meter) wide-field (3.5 degrees) survey telescope, which will be located on the Cerro Pachón summit in Chile. The reflective telescope uses an 8.4 m f/1.06 concave primary, an annular 3.4 m secondary and a 5.2 m concave tertiary. The primary and tertiary mirror aspheric surfaces are located on one monolithic borosilicate substrate, the so-called M1M3 mirror. This unique design offers significant advantages in the reduction of degrees of freedom, improved structural stiffness for the otherwise annular surfaces and provides a very compact design. The secondary mirror is a 100mm thick meniscus convex asphere. The three-mirror system feeds a three element refractive corrector to produce a 3.5 degrees diameter field of view over a 64-cm flat focal surface.

This paper describes the current status of the mirror system components and provides an overview of the upcoming milestones. The future activities, including the mirror coating specifications, the system tests and the integration plan are presented.

9906-21, Session 6

Large Synoptic Survey Telescope mount final design

Shawn P. Callahan, National Optical Astronomy Observatory (United States); Alfredo Orden Martinez, Manuel Perezagua Aguado, Luis Garcia-Marchena, GHESA Ingeniería y Tecnología, S.A. (Spain); Ismael Ismael Ruiz de Argandoña, IK4 Tekniker (Spain); Marco Venturini, Phase Motion Control S.r.L. (Italy); Francisco M. Romero, Ricardo Rodríguez, José Carlos González Gonzále, Asturfeito S.A. (Spain); Sandrine J. Thomas, Chuck Gessner, Michael Warner, Jeffrey D. Barr, Paul J. Lotz, German Schumacher, Oliver Wiecha, George Z. Angeli, John Andrew, Charles F. Claver, William J. Gressler, Bill Schoening, Jacques Sebag, Victor L. Krabbendam, Douglas Neill, Edward A. Hileman, Gary Muller, Constanza Araujo Hauck, LSST (United States)

This paper describes the status and details of the large synoptic survey telescope mount assembly (TMA).

On June 9th, 2014 the contract for the design and build of the large synoptic survey telescope mount assembly (TMA) was awarded to GHESA Ingeniería y Tecnología, S.A. and Asturfeito, S.A.

The design successfully passed the preliminary design review on October 2, 2015 and is currently being detailed for the final design review. This paper describes the detailed design, analytical model results, preparations being taken to complete the fabrication, and the transportation and installation plans to install the mount on Cerro Pachón in Chile.

The telescope mount assembly is designed to provide a low-hysteresis high resonant frequency structure to meet the demanding pointing repeatability requirements required for this telescope.

The TMA is supported on a 19-m diameter steel reinforced concrete pier designed by Arcadis Chile S.A. The azimuth structure is in turn supported on six custom SKF axial and eight radial hydrostatic bearings optimized to provide stiffness. The elevation structure is supported on two trunnions mounted with two pairs of custom SKF radial bearings and two pairs of axial bearings. The oil supply system has been designed by HYDX hydraulic solutions.

The azimuth assembly is driven by sixteen dual-gap linear motors designed by Phase Motion Control. The elevation assembly uses two drive arcs driven by a total of six dual gap motors. The azimuth and both elevation drive arcs are encoded by the latest generation Heidenhain tape encoders.

The top end assembly is attached to the elevation structure by a spider design composed of sixteen truss elements. This rigid assembly supports a removable spindle that supports the 4000 kg LSST camera and the large 5500 kg secondary mirror (M2) assemblies.

The TMA design also supplies all cooling plumbing, refrigerant lines, power, and communication services throughout the TMA. All services are connected to the TMA inside the pier and are routed to the azimuth structure through a motorized may-pole type cable wrap with enhancements based on GHESA's know-how from previous projects. Services are routed to the elevation structure through two passive cable wraps, one on each side of the elevation axis, located over the Azimuth Platforms.

A third motorized cable wrap has been designed by IK4 Tekniker to route all services and utilities to the camera through the camera rotator and hexapod.

The TMA also incorporate light baffles to work in unison with the dome shutter and wind screen.

The latest detailed schedule for the TMA is included to show the milestones for the installation at fabrication facilities at Asturfeito in northern Spain and then on top of Cerro Pachón, Chile. A detailed integration plan is provided showing the planned integration of the telescope in the dome. We are planning for a safe design by using a hazard analysis process and best practice safety standards

This large project is the culmination of work by many people and the authors would like to thank everyone that has contributed to the success of this project.

9906-22, Session 7

The LSST Dome final design

Joseph DeVries, Douglas Neill, Jeffrey Barr, LSST (United States); Gianpietro Marchiori, Simone De Lorenzi, EIE Group s.r.l. (Italy)

The Large Synoptic Survey Telescope (LSST) is a large (8.4 meter) wide-field (3.5 degree) survey telescope, which will be located on the Cerro Pachón summit in Chile. As a result of the Telescope wide field of view, the optical system is unusually susceptible to stray light. In addition, limiting the effect of wind on the Telescope from the environment is important. The rotating enclosure system (Dome) includes a moving wind screen and light baffle system. All of the Dome vents include hinged light baffles, which provide exceptional Dome flushing, stray light attenuation, and allow for vent maintenance access from inside the Dome. The wind screen also functions as a light screen, and helps define a clear optical aperture for the Telescope. Since the Dome must operate continuously without rotational travel limits to accommodate the Telescope cadence and travel, the Azimuth drives are located on the fixed lower enclosure to accommodate glycol water cooling without the need for a utility cable wrap. An air duct system aligns when the Dome is in its parked position, and this provides

air cooling for temperature conditioning of the Dome during the daytime. A bridge crane and a series of ladders, stairs and platforms provide for the inspection, maintenance and repair of all of the Dome mechanical systems. The contract to build the Dome was awarded to European Industrial Engineering in Mestre, Italy in May 2015. In this paper, we present the final design of this telescope and site sub-system.

9906-23, Session 7

The LSST calibration hardware system design and development

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The Large Synoptic Survey Telescope (LSST) is currently under construction and upon completion will perform precision photometry over the visible sky at a 3-day cadence. The relative photometric design specifications of LSST for bright unresolved point sources are 5 mmag in the bvri filters and 7.5 mmag in the uzy filters. Furthermore, the accuracies must be achievable in non-photometric observing conditions. Meeting these requirements poses a significant challenge and necessitates the calibration of systematic errors, such as atmospheric transmission, that evolve both temporally and spatially over the course of a ~2-3 LSST pointings. Similar to other surveys, calibration measurements and corrections must be determined for static effects such as vignetting and system properties that may evolve over longer timescales, such as optical throughput. This paper describes multiple hardware systems that LSST is developing to measure and compensate for numerous sources of systematic errors.

To compensate for the effects of atmospheric transmission and its temporal and spatial variability, LSST will utilize a robotic 1.2-meter diameter auxiliary telescope dedicated to obtaining spectra of main-sequence stars in the immediate vicinity of where LSST is pointed. This paper describes the auxiliary telescope, its enclosure and the spectrograph that has been specifically optimized to characterize the atmospheric transmission properties at high cadence in coordination with the main telescope.

Characterization of numerous optical properties of LSST is accomplished using two independent systems. The first system is a custom-made collimated beam projector that projects a field of sources on to user-defined discrete sections of the telescope optics. This device enables the ability to characterize the spatial dependence of the telescope and instrument transmission function, monitor of filter throughput evolution and assist in the characterization of ghosting effects. The second system is a flat-field screen that will be illuminated by both a white-light and a tunable monochromatic illumination system. These systems will produce data to measure the high-frequency variations in the global transmission function. This paper describes both of these hardware systems and the suite of measurements they are expected perform. Lastly, this paper details numerous smaller pieces of hardware that will conduct environmental monitoring such as a DIMM and GPS precipitable water vapor measuring system.

9906-24, Session 7

LSST summit facility construction progress report: reacting to field conditions and design refinements

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The civil work and buildings for Summit Facility of the Large Synoptic Survey Telescope (LSST) are among the first major elements that need to be designed, bid and constructed to support the subsequent, sequential integration of the dome, telescope, instruments and supporting systems. As the contracts for those other major subsystems move forward there is inevitable and beneficial evolution in their designs, which can result in significant modifications to the early development of the facility and infrastructure.

The contract for construction of the LSST Summit Facility was initiated in January, 2015. Since then, now roughly halfway through construction, there have been some necessary modifications to the facility design resulting from unanticipated field conditions as well as the evolution of interfaces to other major elements of the LSST project – principally the telescope mount, the dome and mirror handling and coating facilities. The modifications related to field conditions have included specifying and testing alternative methods of excavation and contending with the lack of competent rock substrate where it was predicted to be. Changes resulting from interface evolution have included alternate anchor bolting methods for the telescope and dome as well as increases in mass, dimensions, and heat loads of major project components. While these and other changes that have been required are somewhat specific to the LSST project, they also exemplify an inherent challenge in the design and construction of facilities and infrastructure for ground-based astronomical observatories.

Responding to these changing interfaces, and to field conditions as they are encountered, presents challenges during the leading edge of the observatory construction project which require sensible and resourceful solutions to avoid potential schedule, budget and operational problems downstream.

9906-25, Session 7

Final design of the LSST primary/tertiary mirror cell assembly

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The Large Synoptic Survey Telescope (LSST) primary/tertiary (M1M3) mirror cell assembly supports both on-telescope operations and off-telescope mirror coating. This assembly consists of the cast borosilicate M1M3 monolith mirror, the mirror support systems, the thermal control system, a stray light baffle ring, a laser tracker interface and the supporting steel structure. During observing the M1M3 mirror is actively supported by pneumatic figure control actuators and positioned by a hexapod. When the active system is not operating the mirror is supported by a separate passive wire rope isolator system. The center of the mirror cell supports a laser tracker which measures the relative position of the camera and secondary mirror for alignment by their hexapods. The mirror cell structure height of 2 meters provides ample internal clearance for installation and maintenance of mirror support and thermal control systems. The mirror cell also functions as the bottom of the vacuum chamber during coating. The M1M3 mirror has been completed and is in storage. The mirror cell structure is presently under construction by CAID Industries. The figure control actuators, hexapod and thermal control system are under developed and will be integrated into the mirror cell assembly by LSST personnel. The

entire integrated M1M3 mirror cell assembly will the tested at the Steward Observatory Mirror Lab.

9906-26, Session 8

The University of Tokyo Atacama Observatory 6.5m telescope: project overview and current status *(Invited Paper)*

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The University of Tokyo Atacama Observatory Project is to construct a 6.5m infrared telescope at the summit of Co. Chajnantor (5640m altitude) in northern Chile, promoted by the Institute of Astronomy, University of Tokyo. Thanks to the dry climate (PWV~0.5mm) and the high altitude, it will achieve excellent performance in the NIR to MIR wavelengths.

The telescope has two Nasmyth foci where the facility instruments are installed and two folded-Cassegrain foci for carry-in instruments. All these four foci can be switched by rotating a tertiary mirror. The final focal ratio is 12.2 and the telescope foci have large field-of-view of 25 arcmin in diameter.

We adopted the 6.5-m F/1.25 light-weighted borosillicate honeycomb primary mirror and its support system that are developed by Steward Observatory Richard F. Caris Mirror Lab.

The dome enclosure has the shape of carousel, and large ventilation windows with shutters control the wind to flush heat inside the dome. The building with control room, aluminizing chamber and maintenance facilities is located at the side of the dome.

Two cameras, SWIMS for spectroscopy and imaging in the near-infrared and MIMIZUKU in the mid-infrared, are being developed as the first-generation facility instruments. The operation of the telescope will be remotely carried out from a base facility at San Pedro de Atacama, 50km away from the summit.

The construction of the telescope is now underway. Fabrication of the telescope mount has almost finished, and the pre-assembly has been carried out in Japan. The primary, secondary, and tertiary mirrors and their cells have been also fabricated, as well as their cells and support systems. Fabrication of structures of dome enclosure is now underway, and their preassembly in Japan will be carried out in 2016. Construction of the base facility at San Pedro de Atacama has been already completed in 2014, and operated for the activities in Atacama. Both of the two instruments, SWIMS and MIMIZUKU, are at their final stages of development. They are now planned to be transported to the Subaru telescope at Hawaii for the test observations in 2016, and after adjustments, will be transported to Chile. The telescope is now scheduled to see the first light at the end of FY2017.

9906-27, Session 8

San Pedro Martir Telescope: Mexican design endeavour

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The Telescope of San Pedro Martir (TSPM) is a new ground-based optical telescope project, with a 6.5 meters honeycomb primary mirror, to be built in the National Astronomical Observatory (OAN) located in Baja California, Mexico. The OAN, with an altitude of 2830 meters above sea level, is within the five best places for astronomical observation in the world. It is located 1830 m higher than the atmospheric inversion layer with 57% of photometric nights, 80% of spectroscopic nights and, a sky brightness up to 22 mag/arcsec2 .

The TSPM will be suitable for general science projects intended to improve the knowledge of the universe, as established on the Official Mexican Development Plan for Science and Technology 2014-2018. The telescope is mainly supported by two Mexican institutions, the National Autonomous University of Mexico and the National Institute of Astrophysics Optics and Electronics. It is developed by Mexican scientists from the Center for Engineering and Industrial Development. This development is supported by a Mexican-American scientific cooperation, throught a partnership with the Arizona Steward Observatory, and the Harvard-Smithsonian Astrophysical Observatory. M3 Engineering will be encharged of enclosure and building design.

The TSPM will be designed to allow flexibility and upgradeability in order to maximize resources. It will be based in the optical and mechanical design of the MMT and Magellan telescopes. The TSPM primary mirror and its cell will be provided by the Arizona Mirror Lab. The telescope will be optimized from the near ultraviolet to the near infrared wavelength range (0.35-2.5 μm), but will allow up to 26μm. The TSPM will feature a f/5 Cassegrain optical arrangement and four bent arrangements. Additionally, f/5 and f/11 Nasmyth optical arrangements are also considered.

The concept will allow the use of existing instruments like MMIRS and MEGACAM. Available experience from currently working ground-based telescopes will be integrated with up-to-date technology specially for control and information management systems.

Its mount is the well known azimuth-elevation configuration. The telescope total mass is estimated in about 230 metric tones, with a total azimuth load of 190 metric tones including around 110 metric tones as the total elevation load. A tracking error lower than 0.03 arcsec RMS is expected under steady wind up to 24 Km/hr. A pointing accuracy between 10 and 2 arcsec is planned. The TSPM is in its design phase. It is the first large optical ground-based telescope to be designed and developed primary by Mexican scientist and engineers. This endeavor will result in the improvement of the scientific and technical capabilities of Mexico including: complex scientific instruments development, systems engineering and project management for large engineering projects. In this paper, which aims to gather the attention of the community for further discussions, we present the engineering preliminary design, the basic architecture and challenging technical endeavors of the TSPM project.

9906-28, Session 8

ALMA: from early science into full operations

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ALMA is a $1b-class facility for mm and sub-mm astronomy now operating at 5000m altitude in the north of Chile. The 66 antennas and two correlators provide an order of magnitude improvement in both sensitivity and resolution over previous instruments. Astronomy at these wavelengths ranges from gas and dust in galaxies at the highest redshifts in the early universe through to comets and moons in our solar system; these topics are reflected by the wide range of PI proposals now being received by the observatory. The mm and sub-mm wavelength atmospheric windows available at the ALMA site offer the ability to peer into regions where planets, stars and galaxies form, unhindered by obscuration from dust.

ALMA is now moving from Early Science and Commissioning (where restricted capabilities were available to the user) through to full operations and PI science (providing external users with almost all capabilities). The fraction of available time used for testing, commissioning, antenna integration, and other observatory tasks has decreased from >30% down to approaching 10%. During the last year, typical PI science programs used 36-45 12m-diameter antennas and up to 12 7m-diameter antennas. Over 1500 applications were received for the current round (Cycle 3), and we show the breakdown of PI proposals in terms of science, array configuration and observing band. Seven bands ranging from 90 to 900GHz, and multiple array configurations with baselines from approximately 20m to 10km are now being used. The facility aims to be flexible, allowing rapid change of observing frequency depending on the weather conditions, in particular the precipitable water vapour and the phase stability. PI observing is currently classed either as 'standard', where the observing and data reduction is routine and automatic, or 'non-standard', where the observing method is still being refined, and data reduction is not pipelined and can require manual intervention. Standard observing is up to band 7 (380GHz) and baselines to 2km. Non-standard observing currently includes the longer baselines and higher frequencies. Efforts are being made to broaden the coverage of the standard capabilities.

This paper describes the real, on-sky performance of the system, and compare this with the original specifications. This includes observatory-wide aspects such as number of usable antennas, bands, and 'teething problems' experienced during the early observing Cycles. Also we describe the technical performance (such as receiver and system temperatures), the site performance (PWV and phase stability), and the sensitivity of the final images. We also show some of the results from measurements using the extended capabilities during recent campaigns. These include high frequencies (up to 900GHz), long baselines (up to 16km), solar observing, VLBI and polarisation. These push the limit of both the system and the site.

Finally we show some of the exciting new science coming from ALMA. These include images with resolutions down to 20 milliarcseconds, and sensitivities down to 10 microJansky. Both of these are unprecedented in sub-mm astronomy.

9906-29, Session 8

The Greenland Telescope (GLT): antenna retrofit status and future plans

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Since the ALMA North America Prototype Antenna was awarded to the Smithsonian Astrophysical Observatory (SAO) in 2011, the project partners – the Academia Sinica Institute of Astronomy & Astrophysics (ASIAA) and SAO, have been working towards retrofitting the antenna for cold weather operation prior to shipping to Greenland for millimeter and submillimeter VLBI and submillimeter single dish observations. At the Montreal conference in 2014 we reported on antenna recommissioning tests made at the ALMA test Facility in New Mexico, subsequent antenna disassembly, and major retrofitting tasks required to enable antenna operation possible in the extreme arctic environment of the Greenland site.

A project risk review, which was held at ASIAA in Taipei in April 2015, endorsed plans to deploy the antenna to Thule Air Base (TAB) for VLBI operation at 230 GHz prior to installing the telescope at Summit Station for higher frequency VLBI and submillimeter operation. Here we report on progress made towards antenna refurbishment, including design studies, the fabrication of critical components, testing, and readiness for deployment to Thule.

Current plans call for shipping the bulk of the antenna components and subsystems from the U.S. Navy Base at Norfolk, Virginia to TAB during summer, 2016, and for the pre-assembly and testing of major antenna systems before that date. We have secured a site close to the naval dockyard to store, assemble and test all but the main dish; and many of the critical components required to assemble the antenna up to the elevation axis are beginning to arrive.

During early 2016, the antenna pedestal will be assembled, including the new support cone and the azimuth bearing, to the yoke, cabin, and invar cone and elevation bearings. Following assembly and alignment, the antenna will be disassembled into a few large sub-assemblies, of transportable size, with as much cabling, electronics, and insulation as possible left in place. The receiver cabin HVAC will also be assembled and tested.

While much of the antenna base will be assembled at the Norfolk site, the assembly of some critical elements, such as the entire dish, including back up structure and reflector, will only take place at TAB. The GLT team has already been trained on backup structure assembly procedures at Vertex, the prime contractor for this antenna, and the reflector panels can only be assembled once the dish is mounted on top of the antenna mount

Working with the US National Science Foundation, we have identified a site for antenna deployment at TAB; and negotiations are ongoing with Base Command to enable assembly to proceed as soon as the antenna components arrive in Greenland in July 2016. The assembly is expected to last until early spring of 2017, as the reflector panels need to be assembled at the coldest temperature at Thule, during the winter months, in order to maintain good figure for eventual operation at Isi station at the peak of the ice sheet. Antenna and telescope commissioning should proceed through summer and fall 2017, and early science tests are expected to start during the winter.

9906-30, Session 8

The 6.5-m MMT Telescope: status and plans for the future

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The MMT Observatory, a joint venture of the Smithsonian Institution and the University of Arizona, operates the 6.5-m MMT telescope on the summit of Mount Hopkins approximately 45 miles south of Tucson, AZ. The upgraded telescope has been in routine operation for nearly fifteen years and, as such, is a very reliable and productive general purpose astronomical instrument. The telescope can be configured with one of three secondary mirrors that feed more than ten instruments at the Cassegrain focus. The f/9 secondary is used primarily with legacy instruments from the original Multiple Mirror Telescope. The f/5 secondary, together with a multi-element corrector, provides excellent image quality over a wide field-of-view for a more modern set instruments. The deformable f/15 secondary, the first of its kind, provides adaptive optics that enables high spatial resolution studies. Nightly observations are scheduled both classically and in a queue mode. In this paper we provide an overview of the the telescope, its current capabilities, and its performance. We will review the existing suite of instruments and their different modes of operation. We will describe some of the general operations challenges and strategies for the Observatory. Finally, we will discuss plans for the near-term (five years) future including technical upgrades, new instrumentation and routine queue operation of MMIRS and Binospec.

9906-133, Session PS5

Ground-based atmospheric water vapor monitoring system with spectroscopy of radiations at 20-30 GHz and 50-60 GHz bands

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There is a big demand for preventing meteorological disasters such as local heavy rainfalls and significant tornadic storms. We propose a novel ground-based measurement system for atmospheric water vapor based on the observation of radiation spectra at 20 – 30 GHz and 50 – 60 GHz band. Time trends of the water vapor estimates a thermodynamic environment in the atmosphere and cloud micro physics. Short-term forecasting and now casting of severe storms are determined by them. There have been some commercial systems [1] [2]. However, their noise temperatures are 10 times higher than intensity of the atmospheric radiation (~ 20 K in the case of Japanese winter). Maintenance of low physical temperature for instruments drastically improves its noise level because the exiting commercial system are operated at ambient condition. Therefore, our cold receiver system identifies a rapid increase of water vapor before clouds generation. At the frequencies between 20 and 30 GHz, our system measures water vapor as a broad absorption peak at 22 GHz and cloud liquid water. Another 50 - 60 GHz band provides supplement information from an Oxygen radiation which contains vertical profiles of physical temperature of molecules in the atmosphere.

We designed our system as simple as possible to deploy the system on top of high buildings, mountains, and on a deck of ship. Our system has a simple transport optical system which has main mirror and wire grid to separate the radiation signal into lower and higher frequency band. For the construction of the compact receiver system, novel technologies which developed for CMB (cosmic microwave background radiation) observation are applied. In particular, a technology to operate a cryocooler on a rotating system [3] and a radio-transparent thermal insulator [4] are key seeds, e.g., cooling and protection of dew condensation in the optical path. At 20 GHz band, the input atmosphere signal is amplified by a HEMT, spectrum shape is simply measured by using a signal analyzer. The 60 GHz receiver is ambient heterodyne receiver and down-convert to 20 GHz because of radiation from Oxygen is high, it is same order as the radiation of ambient. Cold blackbody calibration source of 50 K is implemented inside of the cryostat. The calibration signal is also transported to each receivers via the wire grid. Our system is designed to be less than one cubic meter and low electrical consumption.

We developed a prototype multi-band band receiver. The receiver noise temperature is about 70 K (350 K) at 20 GHz (60 GHz) band which was confirmed by based on Y-factor measurements with 77 K cooled blackbody. We also demonstrated the monitoring of the atmospheric water vapor and radiations from oxygen molecules along to determine in the zenith. We confirmed opacity by our system is consistent with the result of the balloon-borne observations. In this conference, we will present overview of our system including status of development, and results of long-term monitoring.

[1] http://radiometrics.com/

[2] http://www.radiometer-physics.de/rpg/html/Home.html

[3] S. Oguri, J. Choi, M. Kawai and O. Tajima, Rev. Sci. Instrum., 84, 055116, (2013).

[4] J. Choi, H. Ishitsuka, S. Mima, S. Oguri, K. Takahashi and O. Tajima, Rev. Sci. Instrum., 84, 114502, (2013).

9906-134, Session PS5

GroundBIRD: observation of CMB polarization with fast scan modulation and MKIDs

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Cosmic microwave background radiation (CMB) is an important source of information about the origin of our universe. In particular, large angular scale odd-parity patterns in the CMB polarization, primordial B-modes, are strong evidence for the inflationary universe. GroundBIRD aims to detect them from the ground with novel techniques: high-speed rotation scan system, cold optics, and microwave kinetic inductance detectors (MKIDs). We plan to start observation at Canary Islands in 2017.

The high-speed rotation scan is realized by the operation of the cryocooler on a rotating table. We developed a series of two rotary joints for high-pressure helium gas and electricity lines, which enable connection of helium gas and power supply between the cryocooler on the table and the compressor on the ground. We already achieved cold condition of 0.23 K with a hold time of more than 24 hours under a condition of continuous rotation at 20 rpm. Scan strategy of most ground-based experiments is periodic left–right motion along the azimuth direction. The scan frequency is limited by the mechanical specifications. On the other hand, our rotation scan results in continuous high-speed pointing motion without any deceleration. It allows us a significant expansion of multipole range at 6 < l < 300 while mitigating the effect of 1/f noise.

We hold two mirrors in the cryostat at below 4K. This condition mitigates a radiation noise from the mirror surfaces. The diameter of the aperture window is 30 cm. In shielding from thermal radiation from the aperture, a combination of metal mesh filters (QMC Instruments Ltd.) and radio-transform multi-layer insulations (RT-MLI) is applied. The RT-MLI is a novel thermal radiation blocker. They consist of a set of stacked formed-polystyrene layers. The layers are transparent to radio waves but block infrared radiation. No thermal link is necessary for RT-MLI and the performance of cooling does not vary with the aperture size. This is because its cooling mechanism is radiative cooling similar to conventional MLI. We achieved to maintain the mirrors at 3.4 K on the optical configuration. We also achieved 0.21 K temperature for Helium sorption cooler and demonstrated to operate a MKIDs in the same condition.

MKID is chosen for the focal plane detector array of GroundBIRD. The fast time response (order of 100 us) of MKID is well-matched with our high-speed scan. MKID has another advantage on its scalability because of frequency-division multiplexing readout. The number of readout cables can be kept small, the thermal conduction along the cables is maintained to be small. We plan to observe at 220 GHz (109 pixels) for an understanding of dust emission as well as at 145 GHz (330 pixels) for CMB. We will briefly present about focal plane development, i.e., design and simulation of horn coupled MKIDs, fabrication of them, and their tests.

9906-136, Session PS5

Science-based requirement and operations development for the Maunakea Spectroscopic Explorer

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The Maunakea Spectroscopic Explorer (MSE) is designed to be the largest non-ELT optical/NIR astronomical telescope that will be a fully dedicated facility for multi-object spectroscopy over a broad range of spectral resolutions. We have developed the top level requirements, system architecture and operational concept with close reference to a suite of science reference observations (SROs). The SROs are themselves the result of a detailed re-examination of the science drivers for such a facility in the context of the range of astronomical capabilities anticipated to be available to the international community in the 2025+ era. Here, we discuss this process, the flowdown into technical requirements, and the ongoing science-based development of MSE, with particular reference to the operational concept for the facility.

9906-137, Session PS6

Thai National Telescope beam simulator testbed development status

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The Thai National Telescope (TNT) (latitude 18.573725o N, longitude 98.482194o E, altitude 2457 m) is a Ritchey-Chretien Telescope with a primary mirror diameter ?M1 = 2.4 m, a focal ratio f/10 and a central obscuration Obsc = 0.3. The TNT is the main instrument of the Thai National Observatory (TNO) which is located near the summit of the Doi Inthanon, situated in the Chiang Mai Province of Thailand at altitude 2,457 meters. The median seeing on this site is approximately 0.9" and is remarkably stable on most nights, rarely exceeding 2".

The TNO is located in a tropical region and the observing season with quasi-continuous clear sky conditions from November to April. During this observing season, the observing time is mainly dedicated to the astronomical observations to take profit as much as possible of the clear sky conditions. The nights dedicated to the optical activities are then limited to 2 half-nights per month to characterize and improve the performance of the TNT. We thus decided to develop an optical setup to simulate in laboratory conditions the geometry of the TNT output beam and carefully prepare the test to be performed in real conditions.

The setup comprises the sources, 1 collimator, 1 focusing optics and 1 detector. The sources consist of both LED monochromatic sources and of 1 stabilized tungsten source. These sources cover the full visible and near infrared domains, from ? ≈ 400 nm to ? ≈ 1 ?m that is the typical wavelength range currently used by the TNT instruments. The light emitted by the source is injected inside mono-mode or multi-mode fibers of various core diameters that simulate the star image provided by the TNT on various seeing conditions.

The fiber core is placed at the focal plane of 1 Cassegrain telescope of diameter ? = 200mm, focal ratio F/12 and central obstruction Obsc = 0.3 that collimates the light toward an identical Cassegrain telescope (focusing optics). This telescope focuses the light toward the instrument to be tested. Each telescope is mounted on 1 mount with 4 degree of freedom (2 rotations and 2 translations) that was fully designed and manufactured at NARIT. The setup is fully achromatic, and the focal ratio and the central obscuration are similar to the TNT.

The first application of this setup will be the preparation of the TNT optical alignment. This alignment will consist of measuring the TNT output wavefront over the FOV, calculating the in-field variation of the astigmatism coefficients, assessing and correcting the lateral shift between the mirrors M1 and M2. The TNT beam simulator setup will be used to prepare this activity by adjusting the parameters of the wavefront measurement setup in laboratory conditions and by measuring the on-axis and in-field variations of the beam simulator output WFE. The second application of this setup will be the development and the test of the future instruments for the TNT such as a focal reducer or a spectrograph.

In this paper, we present the setup optical and mechanical design, we describe the optical alignment method, we present the performance and we discuss the future configurations of the setup that will be used to test the future TNT optical instruments.

9906-138, Session PS6

The Cherenkov Telescope array on-site integral sensitivity: observing the Crab

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The Cherenkov Telescope Array (CTA) is the future large observatory in the very high energy (VHE) domain. Operating from 20 GeV to 300 TeV, it will be composed of tens of Imaging Air Cherenkov Telescopes (IACTs) displaced in a large area of a few square kilometers in both the southern and northern hemispheres.

Thanks to the wide energy coverage and the tremendous boost in effective area (10 times better than the current IACTs), for the first time a VHE observatory will be able to detect transient phenomena in short exposures. The CTA/DATA On-Site Analysis (OSA) is the work package devoted to the development of ad-hoc pipelines and algorithms to be used at the CTA site for the reconstruction, data quality monitoring, science monitoring and real-time science alerting during observations.

The minimum exposure required to issue a science alert is not a general requirement of the observatory but is a function of the astrophysical object under study, because the ability to detect a given source is determined by the integral sensitivity which, in addition to the CTA Monte Carlo simulations, providing the energy-dependent instrument response (e.g. the effective area and the background rate), requires the spectral distribution of the science target.

The OSA integral sensitivity is computed here for the most studied source at Gamma-rays, the Crab Nebula, for a set of exposures ranging from 1000 seconds to 50 hours, using the full CTA Southern array. The reason for the Crab nebula selection as the first example of OSA integral sensitivity is twofold: (i) its spectral energy distribution, spanning from radio to gamma-rays, covers the entire CTA energy range, so that the cross-correlation of different IACTs and other instruments (e.g. Fermi and AGILE) is needed to model its emission; (ii) it represents, at the time of writing, the standard candle in VHE and it is often used as unit for the IACTs sensitivity.

The effect of different Crab Nebula emission models on the CTA integral sensitivity is evaluated, with the aim of emphasizing the need for representative spectra of the CTA science targets in the evaluation of the OSA use cases. Using the most complete model as input to the OSA integral sensitivity, we obtain a significant detection of the Crab nebula (about 10% of flux at 5 sigma) even for a 1000 second exposure, for a minimum energy less than 10 TeV.

9906-139, Session PS6

Modal vibration testing of the DVA-1 radio telescope

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The Dish Verification Antenna 1 (DVA-1) is a 15m aperture offset Gregorian radio telescope featuring a rim-supported single piece molded composite primary reflector on an altitude-azimuth pedestal mount. The DVA-1 was completed at the Dominion Radio Astrophysical Observatory (DRAO) in 2014 and has since been used for a variety of engineering tests and observations with excellent performance and results.

Vibration measurements of the DVA-1 telescope were conducted over three days in October 2014 by NSI Herzberg engineers. The purpose of these tests was to measure the first several natural frequencies of the DVA-1 telescope.

Seismic accelerometers were mounted on the antenna structure at specific locations chosen with regard to the analytically predicted mode shapes. Vibratory disturbances were induced by several means: natural wind, step-release of a suspended mass, and impulse hammer impacts. Normal modes were clearly identified by all three methods. Additionally, transfer functions between the azimuth bearing and receiver platform were also obtained. This paper describes the experimental approach, and summarizes some interesting results.

The measured values of the first three natural frequencies were 2.6-2.8Hz, 4.0Hz, and 6.3Hz, agreeing well with available analytical predictions. The range of values associated with the first mode is due to the varying geometery of the altitude drive over its range of motion. Step-release tests were performed at a range of zenith angles, and unexpectedly high damping of the first vibration mode was observed over a narrow range of angles. The likely cause of this phenomenon was determined to be slight mechanical backlash in a single joint located between the dish rim and its support structure, which undergoes a load reversal at that particular zenith angle. This joint has since been adjusted and follow-up vibration measurements are planned to verify that the observed effect has been rectified. The paper will also report these results and any conclusions drawn.

9906-140, Session PS6

A position sensing device for measuring the self-weight load induced displacements of the SRT subreflector

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The Sardinia Radio Telescope (SRT) metrology team is working on the design and test of the devices needed to maintain as high as possible the antenna efficiency and the pointing performances in the safe weather conditions. The SRT is a fully steerable antenna with a Gregorian optical configuration, equipped with a 64 meters diameter active primary mirror (M1) with a focal length to diameter ratio (f/D) of 0.33 and an elliptical shape secondary mirror (M2) of about 8 meters with an f/D of about 2.35. Moreover thanks to a six degree of freedom system (hexapod) the M2 position can be adjust to guarantee the best possible alignment. The optical configuration of the antenna should be maintained with an alignment accuracy of few tenths of millimeter in order to guarantee the optimal antenna efficiency. The SRT homology configuration has been designed to operate up to 22 GHz frequency with a total RMS surface error of about 600 ?m and repeatable pointing errors of about 5 arcmin, without any measurement or correction for deformations affecting the antenna structure. At higher frequencies (SRT has been designed to operate up to 100 GHz), at which gravitational loads and thermal effects become critical for the antenna performances, accurate devices to check, for instance, the M1 and M2 optical alignment are needed.

Here we present a system consisting of a commercial optical position sensing device (PSD) that, coupled with a laser diode, is able to measure the secondary mirror displacement with respect to the telescope optical axis. We will describe the mechanical assembly realized to align the laser diode and to operate the PSD on board the antenna. The PSD has been integrated in M2, modifying the central flange of the subreflector in order to host two devices. The first device, the PSD, allows us to evaluate the shifts on the X-Y plane orthogonal to the antenna optical axis and the tilts of M2 around the X and Y axis, the second device will be soon installed, in order to measure the displacements along the Z optical axis. The laser diode has been installed in a very stable mount, by using a mechanical system that allows a rapid alignment of the laser with respect to the PSD window. The preliminary tests were performed during night time, when the thermal deformation are not critical, firstly aligning the laser on the PSD with the antenna at the zenith and then moving the antenna in elevation in small steps (from 5° to 90°) reading the corresponding M2 deflections by its ideal position. By varying the antenna elevation and acquiring the PSD data, it is possible to evaluate the overall gravitational effects. Our aim is to check the PSD response in operative measurement conditions, then to optimize the antenna pointing capabilities updating the current M2 lookup table. The results of the measurement campaigns will be shown.

9906-141, Session PS6

Characterization of the mechanical properties of the SOFIA secondary mirror mechanism in a multi-stage approach

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The Stratospheric Observatory for Infrared Astronomy (SOFIA) uses its compact and highly integrated Secondary Mirror Mechanism (SMM) to perform chopping, a technique to determine and subtract infrared background radiation from the signal of the astronomical target. The SMM tilts the secondary mirror in a square wave pattern in order to switch between different portions of the sky. The actuation of this square wave chopping also excites various eigenmodes of the tilt chop mechanism. Specifically, a previously unknown mode at a frequency of 300 Hz disturbs and limits the performance of the chopping controller. In order to determine the nature of the excited eigenmodes and to be able to investigate possible countermeasures various test campaigns as well as finite element model analyzes have been performed. As the flight hardware of the SMM on the operational observatory is not generally available for experimental tests, a test bench with mechanical parts identical to the flight hardware has been designed and manufactured, which allows experimental characterization of the structure without taking time away from science operations. The structural dynamics of the test bench model were characterized in several design stages. Additionally in 2014, during SOFIA's heavy maintenance down time, the SMM flight hardware was removed from the telescope for separate inspection and maintenance. This allowed for a modal test campaign directly using the flight hardware while a dummy aluminum mirror was mounted instead of the original silicon carbide mirror with its sensitive optical surface. All tests employed accelerometers placed on the mechanism and the structure was excited with an impact hammer. Additionally, signals from internal position sensors and from the voltage induced by the motion of the electromagnetic actuators of the mechanism were acquired. A detailed finite element model of the SMM has been created, where model parameters were initially derived from design specifications and drawings. These parameters were updated using eigenfrequencies, mode shapes, and damping parameters derived from the test campaigns. This paper reports on the test campaigns and results of the experimental characterization of the various test bench design stages and of the flight hardware. It presents the identification of

mechanical properties from those tests and the correlation of test bench to flight hardware. Further correlation of the rather coarse mode shape vectors of test data to mode shapes derived from finite element models allows for the identification of those vibration modes which are excited during observatory operation and thus limit the chopping performance. By examining the detailed mode shapes derived by finite element modal analysis we identify those parts of the mirror which contribute primarily to the excited mode, even though they could not be equipped with sensors due to their small size or limited accessibility. The results of this characterization serve as basis for improvements for the current SMM as well as for a next generation advanced chopper.

9906-142, Session PS6

The absolute calibration strategy of the ASTRI SST-2M telescope proposed for the Cherenkov Telescope Array and its external ground-based illumination system

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ASTRI is the end-to-end prototype for the CTA small-size class of telescopes in a dual-mirror configuration (SST-2M) proposed by the Italian National Institute of Astrophysics (INAF) in the framework of the Cherenkov Telescope Array. ASTRI SST-2M has been installed at the Serra La Nave Astrophysical Observatory on Mount Etna (Sicily) and its Performance Verification Phase started in autumn 2015. For the relative pixel calibration and gain monitoring, the ASTRI SST-2M camera is equipped with an internal illumination device, while an external, portable, illumination system, placed at a few km distance from the telescope, will be used for the absolute end-to-end calibration of the telescope spectral response. Moreover analysis of signals induced in the camera pixels by the night sky background (diffuse emission and reference stars) will be used to monitor the long term evolution of the telescope calibration. We present an overview of the ASTRI SST-2M absolute calibration strategy and the external illuminating device that will be used for its spectral calibration.

9906-143, Session PS6

System performance testing of the DVA1 radio telescope

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DVA1 (Dish Verification Antenna 1) is an innovative rim-supported single-piece composite-material dish radio telescope developed by the National Research Council of Canada and the US SKA Technology Development Program. It has a feed-high offset Gregorian optical arrangement with a primary surface effective diameter of 15 metres and has been designed for efficient operation to a frequency of at least 10 GHz.

DVA1 has been undergoing mechanical and astronomical system tests since 2014 at the Dominion Radio Astrophysical Observatory (DRAO), with a focus on single-dish performance measurements. Ku band holography measurements of commercial broadcast satellites have been used to measure the effective surface accuracy of the dual-reflector antenna system and to characterize surface stability against thermal, insolation, and wind variations. The measured Ruze efficiency is ~ 0.8 at 10 GHz, indicating good efficiency up to about 20 GHz.

The surface is very stable (~ 10% variation in surface RMS) over the range of environmental conditions able to be tested at the DRAO site.

Astronomical measurements using DVA1 were made in L band using a prototype front end developed for the MeerKAT array by EMSS Antennas in South Africa. Key performance metrics measured in L band include the aperture efficiency, sensitivity (Aeff/Tsys), and tipping curves. The clean shaped optics of the offset Gregorian design, careful attention to feed design, and the high sensitivity of the L band receiver yield a system with high aperture efficiency (~ 0.8), excellent sensitivity (~ 9 m^2/K), and very low spillover contribution to the system temperature. Observations of the 21 cm atomic hydrogen lines towards a number of sources demonstrate the low stray radiation pickup of the antenna.

Testing is ongoing, with a current focus on measuring the polarimetric performance of the antenna on polarized continuum sources and Zeeman observations of 21 cm line sources.

9906-144, Session PS6

Mirror coating and cleaning methodology to maintain the optical performance of the GTC telescope

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This paper presents a strategy to optimize GTC telescope optical performance in terms of reflectivity and scattering by means of a suitable combination of mirror coating, CO2 and in-situ cleaning. The analysis is based on repetitive measurements made with an accurate reflecto-scatterometer plus an evolutional model for dust effects over mirror surfaces. The fact that GTC primary mirror is segmented implies specific difficulties to determine the total improvement in image quality compared with a monolithic mirror. Factors such as frequent presence of calima (Saharian dust), optical improvement due to segments recoating and the effects of mirror orientation were also studied. According to our experience, a monthly period of CO2 cleaning was established, except during episodes calima, when a shorter weekly period is much more appropriate. Trends of the main optical parameters (reflectivity at different wavelengths and total integrated scattering) were recorded and analyzed to identify causes for the variation of the mirrors performance. The data also reveals an evolution of the yearly weather conditions. Results presented include the time evolution of the reflectivity and the improvement due to the presented practices for mirror maintenance. An additional degradation of optical parameters appears due to environmental factors. In this sense, lack of cleaning in presence of calima and/or high humidity reduces the effectiveness of the cleaning method. The total reflectivity results from combination of three optical surfaces, hence thresholds were set for individual components and used to select the mirrors to replace and clean. Historical data about total reflectivity is correlated against optical OSIRIS zeropoints evolution and a non-linear relation was established. This relation is applicable for the periods where real measurements are not feasible. Furthermore, an innovative reflectivity measurement method for a segmented mirror is proposed based on zeropoint measurement of unstacked primary. This new method will allow more frequent control of the individual segments relative reflectivity. This will easily disentangle the impact of the different environmental factors from maintenance practices. In that way, their effects over the total instrument throughput will be quantified. Maintenance of telescope optical quality and observing time availability compete for resources, and a suitable trade-off between these should be achieved in order to increase the overall productivity. Finally, to preserve optimal performance

operational limits for environmental conditions, like density of dust, were established.

In summary, a method for measuring optical quality of large segmented telescope has been designed and suitable data processing tools developed. Periodical measurements were recorded for over six years and results analyzed. These data allows us to propose suitable environmental thresholds, optimal mirror cleaning and components replacement rate. All these achievements improve the overall system and observing performance. Likewise they are a valuable baseline for the future large-aperture segmented-mirror telescopes.

9906-145, Session PS6

Antenna pattern characterization of the low-frequency receptor of LOFAR by means of an UAV-mounted artificial test source

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In a few years time, the Square Kilometre Array (SKA) will become the most powerful radio telescope on Earth, surpassing the sensitivity of existing instruments by an order of magnitude and able to produce images with extremely high dynamic range. The calibration of SKA is of fundamental importance to successfully achieving the expected performance and it poses significant challenges from different points of view. In particular, instrumental calibration involves accurate electromagnetic (EM) characterization of the array in the real operating conditions. At low frequencies, this is more difficult due to the strong mutual coupling with the environment and due to the fact that it is practically impossible to measure the system in anechoic chambers.

In this perspective, we developed an original system consisting of a radio frequency transmitter mounted on an Unmanned Aerial Vehicle (UAV) for the characterization and calibration of Low-Frequency Aperture Arrays (LFAAs). This artificial source has proved to be a reliable and accurate system for characterizing embedded element patterns and array patterns of the Medicina Array Demonstrator [1] and in the context of the aperture array verification systems of SKA [2]. Recently, interest arose for using this system in the Low Frequency Array (LOFAR), an operational aperture array telescope that is also a pathfinder of the low-frequency element of SKA phase 1. LOFAR consists of about 50 stations spread all over Europe. Each station is composed of two subarrays, each with a different type of dual-polarized receptors: the Low Band Antenna (LBA) and the High Band Antenna covering respectively the frequency range between 10 and 80 MHz and between 120 and 240 MHz.

In this contribution, we show several experimental results obtained by measuring the antenna patterns of the LBA. This activity has been performed to achieve a certain degree of confidence before measuring the embedded element patterns of a complete LOFAR station. In these measurements, the UAV system was used at such low frequencies (below 100 MHz) for the first time. The frequency range of the LBA made this campaign challenging since the antenna on the UAV is not matched (even if it is quite large) below 60 MHz. Therefore, a careful characterization of the test source gain has been performed in order to measure the absolute gain of the LBA. The experimental results, which include both the co-polar and the cross-polar patterns at different frequencies, are in excellent agreement with full-wave EM simulations.

[1] G. Pupillo, et al., "Medicina Array Demonstrator: Calibration and Radiation Pattern Characterization Using a UAV-Mounted Radio-Frequency Source," Experimental Astronomy, vol. 39, 2, pp. 405-421, 2015.

[2] F. Paonessa, et al., "UAV-based pattern measurement of the SKALA," IEEE Antennas and Propagation Society International Symposium, (Vancouver, BC, Canada), July 19-24, 2015.

9906-146, Session PS6

Re-aluminising the South African Astronomical Observatory's 74-inch primary mirror

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Telescope mirrors are subject to relatively harsh environments and thus require periodic re-aluminisation to maintain their reflectivity. The mirrors also need to be carefully replaced and/or re-aligned to avoid having coating-related throughput gains reduced by subsequent optical misalignment and image quality degradation. The SAAO's Sutherland field station suffers from two environmental challenges: dust and frequent bouts of high humidity when the south-east wind drives moisture rich air up over the observing plateau, often rapidly forming thick orographic cloud. Dust settling on the mirrors thus ends up adhering to the upward-facing optical surfaces and this sticky layer is not removed by CO2 cleaning. The 74-inch primary mirror was unsuccessfully re-aluminised in April 2015. Certain parts of the mirror proved difficult to clean and the resulting coating included rough, hazy white patches where those problem areas had been. Dreading that the patches might indicate that the optical surface had been etched, we used cotton wool soaked with ferric chloride to strip the coating in a couple of small areas. To our immense relief, we confirmed that the problem was restricted to the coating. The aluminising equipment for the 74-inch dates from 1959 and an inspection of the aluminising lab situated beneath the telescope triggered an extensive overhaul of the system. The vacuum tank was thoroughly cleaned and the severely degraded o-ring was replaced. The tungsten filaments in the tank were replaced and all of their connections checked and tightened as required. A new vacuum gauge was installed and the roughing and diffusion pumps were serviced. One of the two diffusion pumps had developed multiple leaks which were traced and repaired. That pump also needed oil and a new o-ring. Given all that had been wrong with the hardware at the time, the quality of the April coating was actually quite impressive! The spruced up aluminising system was put through its paces in mid-November 2015 using a few small mirrors that had been appropriately stripped, cleaned and prepared. This trial-run was successful and so we proceeded to redo the 74-inch primary in late November, using the same de-ionised water, potassium hydroxide, sodium lauryl sulphate, cotton wool, safety gear and cleaning techniques employed by the mirror coating team at the neighbouring Southern African Large Telescope (SALT). The new coating looks superb and an on-sky image quality assessment using bright defocused stars confirmed that the primary required no tip/tilt adjustment. We used SALT's Ocean Optics reflectometer to quantify the improvement in reflectivity. Measurements made on different parts of the dirty primary ranged between 20 and 70%, while the new coating uniformly exceeded 90% at the reference wavelength of 320 nm. The resulting increase in telescope throughput will also be evaluated quantitatively, using spectroscopic domeflats and spectro-photometric standard star observations obtained with our recently upgraded Cassegrain spectrograph (SpUpNIC) before and after the re-aluminising. Our next task will be to re-aluminise the 74-inch secondary and then optically re-align the telescope using the new 74-inch alignment procedure and associated hardware developed in early 2015.

9906-147, Session PS6

Characterization of friction in the 3.6 m Devasthal optical telescope

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In this paper, we present friction characterization of the 3.6 m Devasthal optical telescope installed in the year 2015 at Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital. The telescope azimuth axis is supported on a hydrostatic bearing while the altitude and rotator axes are supported on hydrodynamic bearings. Both altitude and azimuth axes are driven directly by high power brushless D.C (BLDC) motors and the rotator is driven by BLDC motor via a gearbox. This system is designed by Advanced Mechanical and Optical Systems (AMOS), Belgium and tuned to achieve tracking accuracy better than 0.1 arcsec RMS. Friction poses control related problems at such low speeds hence it is important to periodically characterize the behaviour at each axes. Compensation is necessary if the friction behaviour changes over the time and starts dominating the overall system response. For identifying friction each axis of telescope is rotated at different constant speeds and speed versus torque maps are generated. The LuGre model for friction is employed and nonlinear optimization is performed in Matlab to identify the four static parameters of friction. The behaviour of friction for each axis is presented and the results are discussed.

9906-148, Session PS6

Collimating the Gemini telescopes using a peripheral wavefront sensor

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We have developed an improved technique to collimate the Gemini telescopes using the Peripheral Wavefront Sensors (PWFS) to measure focal plane offset and tilt. For several years prior to 2014, observers at Gemini North noticed a variation in the focus Zernike term of about +/-30 µm when guiding with the PWFS. This variation was originally attributed to a tilt of the PWFS rotary table, and plans were made to shim the table. Further testing, however, revealed that it was actually due to an incorrect tilt of the secondary mirror (M2), causing the curved focal plane to be both offset and slightly tilted relative to the PWFS axis. Gemini's normal tuning technique adjusts the M2 offset to remove coma. Due to the coma insensitive Ritchey-Chrétien design of the telescopes there is no Seidel comatic field pattern typical of an aligned telescope. Instead a constant comatic field pattern occurs from either tilt or decenter of M2, and patterns arising from tilt can be eliminated with the appropriate decenter. For the Gemini telescopes, a zero-coma condition alone does not guarantee proper telescope collimation. The new technique measures PWFS focus variation around the periphery of the imaging field, 6 arcminutes off-axis, by programming the telescope pointing to move in a circle while PWFS tracks a guide star, completing a full circle in about 20 minutes. The measured focus variation is then used to infer the focal plane offset and corresponding M2 tilt, and the tilt and decenter offset are then adjusted to zero both focus variation and coma and achieve true collimation. The technique permits correction of the erroneous M2 tilt to <~ 30 arcseconds, corresponding to a wavefront error <~ 3 µm, limited by short-period variations of the focus.

9906-149, Session PS6

Simulation of the wavefront sensing of the active primary mirror system for the 2.1-m telescope of the SPMO

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In this work we present a simulation of the wave-front sensing of the active primary mirror system for the 2.1-m telescope of the San Pedro Mártir's Observatory (SPMO) by Non-Linear Curvature Wave-front Sensing (nl-CWFS). The active cell from the SPMO have a passive support system intended to allow us to induce and correct deformations of azimuthal frequency 2 and 3, such as astigmatism and comma, according to their Zernike expansions. The purpose of the active system is to control the pressure in each of the 18 actuators (air bags) so that the load carried and the desired deformation and position of the mirror are kept to their desired values. For that, measuring the wave-front produced by the active primary mirror is an important task to do, so that the best performance of the active cell can be assured. The nl-CWFS method is derived from the curvature wave-front sensing (CWFS) concept but using a non-linear phase retrieval wave-front reconstruction procedure. This technique offers a method that can be performed without having to include extra equipment to the telescope delivering high precision measurement. Different wave-front techniques have been employed on this telescope's active cell and now the nl-CWFS is going to be simulated, waiting for a future work with experimental images. The active cell is going to be tested by changing its actuators values. In each active cell state, defocused images from either focal plane are simulated and the wave-front reconstruction is performed by using the Gerchberg-Saxton (GS) phase diversity algorithm. The GS algorithm is an iterative phase retrieval scheme which requires a pair of light distributions in defocus pupil planes. The wave-front is propagated via Fourier Transform (Fresnel propagation) from one pupil plane to another and the phase information at the resulting propagated plane is preserved while the known pupil plane amplitude is used to apply constrains to the next wave-front propagation. The algorithm begins with an estimate of the first light distribution, with a phase that usually is taken to be zero or any random value. The wave-front is iteratively propagated between the defocused planes until the phase extracted between propagations converges. The telescope simulations are performed by ZEMAX and MATLAB working together. In ZEMAX the model of the 2.1-m telescope of the SPMO is used to obtain the information of the Zernike Polynomials in a specific position in the detector while the defocus images are created by moving the secondary mirror up and down. The MATLAB code simulates the effect of the active cell in the primary mirror and introduced to the ZEMAX file, then the routine will extract the Zernike Polynomials generated to simulate the defocus pupil images. The wave-front reconstruction algorithm is discussed, the system's configuration used in each simulation, the detector properties, and error obtain from the measurement are mentioned. Our main interest is to study the measure the wave-front of the telescope, the sensitivity of the method, considerations that have to be taken into account related with seeing conditions, and considerations from sampling conditions.

9906-150, Session PS6

Addressing chronic operational issues at the W. M. Keck Observatory

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The W. M. Keck Observatory (WMKO) has a good track record at addressing large critical faults which impact observing. Our performance tracking and correcting chronic minor faults has been mixed, yet this class of problems has a significant negative impact on scientific productivity and staff effectiveness. We have taken steps to address this shortcoming. We describe the creation of a program to identify, categorize and rank these chronic operational issues, track them over time, and develop management options for their resolution. The success of the program at identifying these chronic operational issues and the advantages of dedicating observatory resources to this endeavor are presented.

9906-151, Session PS6

Point-diffraction interferometer for radio telescopes

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We propose a novel wavefront sensor in radio bands with a point diffraction interferometer (PDI) which is one of the wavefront sensors. A small object to work as a point source divides an incident wave into a reference wave and a test wave. Wavefront errors can be estimated with interferograms of the two waves.

Millerd et al. (2004) and Imada et al. (2015) discussed PDIs using a polarizing point-diffraction beam splitter (PPBS). The PPBS has a polarizing pinhole at its center, while the other region than the pinhole has a different polarizing property from that of the pinhole. The beams passing through the pinhole and the other region are orthogonally polarized, and work as the reference beam and the test beam, respectively, since only the latter carries wavefront errors from the upper stream. Millerd et al. (2004) demonstrated a PDI with the PPBS at a focal plane and a phase mask attached to a detector array at a pupil plane. It is assumed that amplitude and phase changes are very little in a small region. Interferograms are collected with each unit cell comprised with four pixels in the phase mask that provide four discrete phase shifts. Imada et al. (2015) proposed another system using both of the reflected and transmitted beams split by the PPBS. A Savart plate is put on each beam path, while one of the paths has a quarter-wave plate. The Savart plate makes a phase difference of pi radians and quarter-wave plate introduces pi/4 shift, then interferograms with four different phase shifts are obtained simultaneously. Since the reflected and transmitted beams are utilized, this method needs an ordinary camera instead of the pixelated unit cells seen in Millerd's method and can achieve higher precision and efficiency, though the optical system become more complicated.

In this work, we propose a new PDI method with a certain kind of detector array which enables an optical system to be free of sophisticated optical elements (e.g., the phase mask or quarter-wave plate). An optical system proposed here has one lens and PPBS only, and needs either the transmitted or reflected beam. The reference and test beam can be split via polarizations and guided to a superconducting delay circuit with slot antennas. The circuit modulates the phase of the reference wave by 0, pi/2, pi, and 3pi/2 radians; we can take four interferograms of the reference and test beams with different phase shifts, simultaneously. It is shown that a complex Fourier transform can be obtained with the interferograms at the plane of the detector.

Let us consider a case where the PPBS is set at a pupil plane and the detector array at a focal plane. In this case, a complex Fourier transform of the electric field at the pupil plane can be obtained at the focal plane. We can measure wavefront errors due to the optical system of an operating telescope if we install a detector array proposed and a PPBS without any other modifications.

9906-152, Session PS6

Temporal characterization of Zernike decomposition of atmospheric turbulence

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Atmospheric turbulence limits the performance of ground-based surveys such as the future Large Synoptic Survey Telescope (LSST). LSST uses an active optics system to adjust the alignment of the secondary mirror and camera and the optical figure of both the secondary and the primary/tertiary mirrors to restore the optics towards its optimal setting in response. The operation of this system depends critically on the covariance matrix for the measurements, in this case coefficients of Zernike polynomials describing the pupil-plane wavefront, which encapsulates the amount of noise present in the control system. While currently, LSST estimates the covariance matrix from Kolmogorov atmospheric turbulence simulations, ideally this should be supported by data. Using pseudo-open loop phase maps, reconstructed from deformable mirror commands obtained from the Gemini Planet Imager Adaptive Optics telemetry, estimates are made for the variation in wavefront, as a function of the spatial and temporal frequencies. This analysis is done by performing Zernike polynomial fits to the instantaneous phase maps, and calculating the resulting temporal power spectra for each Zernike coefficient. The time averaged covariances, over 60 second observations, are calculated and compared to the results of the Kolmogorov atmosphere simulations currently used by LSST. Longer time-series exposures allow for a characterization of how the wavefront variation due to atmospheric turbulence average over different time-scales, through study of the Zernike variances as a function of averaging time. Noticeable deviations from the Kolmogorov simulations have been observed in the scale of the Zernike coefficient variances, and the spatial and temporal spectral density power exponents.

9906-153, Session PS6

A new telescope control system for the Telescopio Nazionale Galileo II: azimut and elevation axes

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TNG is a 4m class active optics telescope at the observatory of Roque de Los Muchachos. In the framework of keeping optimum performances during observation and continuous reliability the telescope control system (TCS) of the TNG is going through a deep upgrade after nearly 20 years of service. The original glass encoders and bulb lamp heads are substituted with modern steel scale drums and scanning units. The obsolete electronic racks and computers for the control loops are replaced with modern and compact commercial drivers with a net improvement in the tracking error RMS. In order to minimize the impact on the number of nights lost during the mechanical and electronic changes in the TCS the new TCS is developed and tested in parallel to the existing one and three steps will be taken to achieve the full upgrade. We describe here the second step that affected the main axes of the telescope, AZ and EL.

9906-154, Session PS6

The first Aluminum coating of the 3700 mm primary mirror of the Devasthal Optical Telescope

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The modern day very large telescope mirrors are a marvel of engineering and glass making, having a very precise curved shape and surfaces polished to within a few wavelengths of light. These large mirror surfaces are covered with a thin layer of highly reflecting material (normally aluminium/silver), ensures approximately 90% of the photons from stars impinging on the mirror to be registered by the sensitive telescope instruments. The optical telescope mirror coatings used in the observatories get damaged and tarnished over time due to oxidation, humidity, dust, impact of charged particles from space etc. In order to maintain the accuracy of observations these mirrors must be recoated frequently. For this purpose the Coating plant to do the aluminium coating on primary mirror of the 3.6m Devasthal Optical Telescope is installed by HHV, india and commissioned in the extension building of the telescope. The coating unit consists of a vacuum chamber fabricated out of stainless steel, with 2 halves, torrispherical dished ends welded with flanges, top lid sits on the bottom chamber separated by two viton O-rings. Motor controlled wiffle tree assembly is in the bottom chamber for rotating the mirror while coating process. Magnetron sputtering technique (one of the PVD methods) is used for the coating. Sputtering is a plasma-assisted technique that creates a vapor from the source target through bombardment with accelerated gaseous ions (typically Argon). To do this the coating chamber is evacuated with the help of rotary, roots and cryo pumps to get vacuum of 10^-6 mbar level before coating and ion beam cleaning. A washing unit is also installed for cleaning of the primary mirror. Initially the primary mirror of the 3.6m Devasthal Optical Telescope is uncoated polished zerodur glass blank supplied by LZOS/AMOS. The primary mirror is cleaned very carefully with the help of diluted acidic, basic solutions and distilled water. The primary mirror is handled with the help of 10 ton cranes and mirror handling tool to place it on wiffle tree of the washing unit as well as the coating chamber. We did proper rehearsal with dummy mirror prior to the actual mirror. Ion beam cleaning of the primary mirror is done for 35 minutes at vacuum level of 10^-2 mbar using rotary and roots pumps for good adhesion of the coating. Magnetron sputtering is done at a vacuum of 10^-3 mbar for the aluminium deposition for 100 minutes with the waffle tree speed of 2 RPM. Argon gas is used in the ion beam cleaning and the magnetron sputtering. Reflectivity and its uniformity, coating thickness and its uniformity measurements have been done in our optics lab and in HHV. We got the reflectivity of the samples is around 85-88%. The thickness of the samples is 102nm +/-3nm which is supposed to be 100nm+/-5nm over the wavelength range from 400-1000nm. For this test we have used the samples of size 75X25X1.5 mm by placing on a holder with the seperation of around 150 mm. Initially sputtering is run for 75 minutes with 5kW power of magnetron, later the sputtering is done for 100 minutes with the same power to achieve the proper optical density. The coating thickness of the samples is measured with optical profiler, stylus profiler and the reflectivity is measured by VW-experimental set up in optics lab and also with Perkin elmer spectrophotometer. Scotch tape pull test is done to verify adhesivity of the coating. We present here a brief description of the coating plant, Mirror cleaning and coating procedures and the testing results of the samples.

9906-155, Session PS6

Temperature characterization of the CITIROC front-end chip of the ASTRI SST-2M Cherenkov camera

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The Cherenkov Imaging Telescope Integrated Read Out Chip, CITIROC, is the chip adopted as front-end for the focal plane camera of the Cherenkov telescope ASTRI SST-2M, proposed as small size telescope for the CTA observatory.

The telescope, operating in the energy range from a few TeV up to 100 TeV, is characterized by innovative technological solutions. The optical system is arranged in a dual-mirror configuration and the focal plane camera consists of a matrix of multi-pixel silicon photo-multipliers. Among others, one of the most important project issue consists in the thermal characterization of the entire camera.

While the ASTRI SST-2 M prototype camera is thermo controlled in a narrow temperature range, in the new generation Mini-Array cameras the thermal control could be relaxed with a considerable gain in terms of power consumption, cost and simplicity. So, a study of the temperature dependence of the camera components is needed. The present work addresses this issue showing the results of the measurements carried out to study the behavior of CITIROC as a function of the temperature. We investigated the pedestal stability, the linearity of the charge output signal, the gain and the trigger uniformity in the temperature range 15-30 °C. Our results show, for the above-mentioned characteristics, that the measured differences varying the temperature, are at the level of a few percent.

9906-156, Session PS6

Delivery, installation, on-sky verification of Hobby Eberly Telescope wide-field corrector

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The Hobby-Eberly Telescope (HET), located in West Texas at the McDonald Observatory, operates with a fixed segmented primary (M1) and has a tracker, which moves the prime-focus corrector and instrument package to track the sidereal and non-sidereal motions of objects. We have completed a major multi-year upgrade of the HET that has substantially increased the pupil size to 10 meters and the field of view to 22 arcminutes by deploying the new Wide Field Corrector (WFC), new tracker system, and new Prime Focus Instrument Package (PFIP). The focus of this paper is on the delivery, installation, and on-sky verification of the WFC, of which fabrication was sub-contracted to the College of Optical Sciences at the University of Arizona. We details the transportation from Tucson to the HET, on-site ground verification test results, post-installation static

alignment among the WFC, PFIP, and M1, and on-sky verification of alignment and image quality via deploying multiple wavefront sensors across 22 arcminutes field of view. The new wide field HET will feed the revolutionary new integral field spectrograph called VIRUS, in support of the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX), a new low resolution spectrograph (LRS2), an upgraded high resolution spectrograph (HRS2), and later the Habitable Zone Planet Finder (HPF).

9906-157, Session PS6

Progress on the 1.8m Solar Telescope: the CLST

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In order to study some special solar activities, such as the emergence, evolution and disappearance progress of the sunspot and magnetic flux, and the key role of magnetic field, a new 1.8-meter size high-resolution solar telescope —the CLST will be built in the Institute of Optics and Electronics(IOE), Chinese Academy of Science(CAS). The CLST has a classic Gregorian configuration, alt-azimuth mount, retractable dome. A 1.8m primary mirror with honeycomb sandwiches structure made by using ULE material will reduce about 70% of weight. Thermal controlling system will also be equipped for the CLST, which including Heat-Stop, primary mirror, tube truss, mount and the other optics elements. An experimental system for validating thermal controlling of primary mirror and Heat-Stop has been built, and the temperature tracking results will be illustrated in this paper. Currently, we have finished the detailed design of the CLST, and some important components also have been manufactured and finished. According to our scheduler, the CLST will be finished in 2017. In this paper, we describe some important progresses and the latest status of the CLST project during these two years. Certainly, the future plan will also be described in our oral report.

9906-158, Session PS6

Sky pointing direction reconstruction resolution studies for a precision pointing device for the large-size telescopes of the Cherenkov Telescope Array

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The performance of an optical camera system is characterized with respect to its suitability to serve as a sky pointing direction monitoring device for the 23-m diameter Large-Size Telescopes (LST) of the future Cherenkov Telescope Array (CTA). Test data sets of sky pictures taken with a sensitive commercial CCD camera (Allied Vision Technologies BigEye B-132G) in combination with a commercial wide-field lens (Walimex Pro 85mm f/1.4) are analyzed with the astrometry.net software package. The accuracy of the image center sky coordinate reconstruction is studied under varying conditions for test data set taking and compared with science requirements imposed for CTA and LST. Conclusions with respect to the performance and limitations of the investigated experimental setup to serve as a precision monitoring device for the LST telescopes of the planned CTA observatory are drawn.

9906-159, Session PS6

The Stratospheric Observatory for Infrared Astronomy (SOFIA) at full operational capability: status and performance

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The Stratospheric Observatory for Infrared Astronomy (SOFIA) has completed major development activities, and it has transitioned into full operational status. With the completion of three observing cycles and the acquisition of a large engineering data set we are able to make a comprehensive assessment of the observatory performance and capabilities. This paper describe the current status of the observatory with an emphasis on its mission performance. We focus on certain areas such as image stabilization, pointing, and tracking which pose specific challenges to the Observatory.

9906-160, Session PS6

Experimental studies on near-field holographic antenna measurement

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Dome A 5m Terahertz Explorer (DATE5) is a proposed telescope to be deployed at Dome A, Antarctica. According to the conceptual design of DATE5 antenna, error budget allocated to the reflector panels setting is no more than 5 microns rms, which is very challenging for on-site surface measurement. Near-field radio holography may be the best way for DATE5 surface measurement for panel adjustments to meet the accuracy requirement.

A near-field radio holography system operating in the 3-mm waveband have been developed as a prototype for DATE5. The dual-channel receiver frontend unit is mounted in the vicinity of the primary focus of an antenna under test, with a signal horn illuminating the reflector and a reference horn, mounted back to the signal horn, pointing to a near-field transmitter. The local oscillator is also mounted in the frontend unit.

Experimental measurements at 92 GHz have been made on a 1.45-m test antenna which is a single-piece parabolic dish made from CFRP sandwich. The transmitter is located 63 m away from the antenna on a tower, with an observing elevation around 19 degrees. The experiments show that, during the night time at which the ambient temperature doesn't vary rapidly, a 75-minute repeatability (repeating measurement 3 times) of ~2.3 microns rms has been achieved, with an aperture spatial resolution of 46 mm. In order to measure a known surface change we attached a piece of aluminum foil with a thickness of 43~47 microns to the reflector. By making difference between the holographic measurements before and after the foil attached we obtained a surface change of approximately 45 microns at the foil position, which met with the foil thickness. Random errors of the experiment system, such as the pointing error, the amplitude and phase variations of the correlation receiver, have been evaluated and their contributions to the derived surface error have been simulated, indicating that the relatively poor pointing accuracy of the test antenna pedestal is the major contribution to the repeatability, and better repeatability will be expected if the pointing accuracy improves.

During the holographic data processing, we need to fit and remove 6 phase terms (constant, 2 linear gradients in the horizontal and vertical directions, 3 focus translations) from the aperture field. These terms account for a phase offset, an antenna pointing error and a small vector displacement of the signal horn relative to the nominal position. After long-time repeated measurements we have observed regular variations of the

fitted terms, that we believe to be correlated with the ambient temperature and sunshine direction. This implies that if the temperature distribution of the antenna structure are measured simultaneously, we can by this means obtain the relation of the structure temperature distribution to the variation of pointing and optimum signal horn position. This is very helpful for a telescope to improve the pointing accuracy and aperture efficiency, and also for verifying the related finite element analysis.

9906-161, Session PS6

Mechanical analysis and measurement of wheel-rail contact system in large aperture radio telescope

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The azimuth rotating part of a large aperture radio telescope usually apply one wheel-rail system; therefore, the impact of wheel-rail pointing errors and the problem of wheel-rail wear are very important to the antenna's point accuracy. This paper first discusses the wheel-rail rolling contact theory and some specific features in large aperture radio telescope. Then builds one 3D model of wheel-rail contact system according to the parameters of 50m antenna in China, and analyzes it by one whole body in MSC.Patran/Nastran. Next we use the multi-body dynamic method to build the model of wheel-rail and simulate it in RecurDyn software. We compare the two results and find that the coupling of rigid-body and soft-body is more important to the contact deformation. And also the results point out the crevice's influence on the mechanical properties of wheel-rail contact system. Finally by some experiments and measurements of 50m antenna, we present some useful measurements for large aperture radio telescope and the testing results show that the multi-body dynamic method is more suitable to the mechanical analysis of wheel-rail contact system.

9906-163, Session PS6

The Huntsman Telephoto Array: low surface brightness imaging with COTS optics

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The Huntsman Telephoto Array is a dedicated imaging telescope assembled from an array of commercial off the shelf (COTS) optics. The primary science goal is the study of the signatures of galaxy formation through low surface brightness imaging. Simulations of galaxy formation predict an abundance of structures such as streams, shells, tails and dwarf satellites however they generally have very low surface brightness which makes them difficult to observe at distances much beyond the Local Group, where resolved star counts become impractical and integrated starlight imaging must be used. The ultimate sensitivity of low surface brightness imaging such as this is typically limited by systematic errors rather than photon statistics, e.g. scattered light and internal reflections, sky subtraction and flat fielding errors. There is evidence that small telescopes can have an advantage over large professional telescope in terms of lower instrumental systematics, and the competitiveness of small COTS optics for low surface brightness imaging has been demonstrated by the Dragonfly Telephoto Array. Dragonfly is based on an array of 10 Canon 400mm f/2.8 telephoto camera lenses and has achieved impressive results, such as the discovery of a new class of 'Ultra-Diffuse Galaxies' in the Coma cluster. Huntsman provides a similar observing facility for the southern skies while also serving as a testbed for long duration side-by-side comparisons of COTS optical equipment. While the majority of the observing time will be dedicated to the primary programme of low surface brightness imaging in g' and r' bands we anticipate narrowband imaging during bright time and Huntsman will also contribute to the optical follow up of gravitational wave detections from the LIGO/Virgo consortium.

In its initial configuration the Huntsman Telephoto Array incorporates an array of 5 Canon 400 mm f/2.8 telephoto lenses equipped with SBIG STF-8300M CCD cameras with a field of view of 2.6 x 2.0 degree and one 11 inch Celestron Rowe-Ackerman Schmidt Astrograph (RASA) with FLI Microline ML11002 camera with a field of view of 3.3 x 2.2 degrees. The system has an overall collecting area of 0.12m^2 and etendue of 0.76m^2 deg^2 and we plan upgrades this year which will increase the collecting area by a further 50% and double the etendue. The telescope is very cost effective due to maximal use of COTS components. The optics, CCD cameras, telescope mount, telescope dome, dome control system and other electronics are all standard commercial items. The only custom components are support structures for the optics, camera mounting adaptors and optical bandpass filters. Total hardware costs for the project have been approximately AUD $200,000. The Huntsman is currently undergoing commissioning at Siding Spring Observatory in Australia.

9906-164, Session PS6

The Blanco Telescope and its instruments: a status report

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In recent years the V. M. Blanco 4-m telescope at Cerro Tololo Inter-American Observatory (CTIO) has been renovated for use as a platform for a completely new suite of instruments: DECam, a 520-megapixel optical imager, COSMOS, a multi-object optical imaging spectrograph, and ARCoIRIS, a near-infrared imaging spectrograph. This has had considerable impact, both internally to CTIO and for its wider community of observers. In this paper, we report on the performance of the renovated facility, ongoing improvements, lessons learned during the deployment of the new instruments, how practical operations have adapted to them, unexpected phenomena and subsequent responses. We conclude by discussing the role for the Blanco telescope in the era of LSST and the new generation of extremely large telescopes.

9906-165, Session PS6

The 3,6 m Indo-Belgian Devasthal Optical Telescope: performance results on site

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AMOS SA has been awarded the contract for the design, manufacturing, assembly, tests and on site installation (Devasthal, Nainital in central Himalayan region) of the 3.6 m Indo-Belgian Devasthal Optical Telescope (IDOT).

The telescope has Ritchey-Chrétien optical configuration with one axial and two side Cassegrain ports. The meniscus primary mirror is active and it is supported by pneumatic actuators. The azimuth axis system is equipped with hydrostatic bearing.

After successful factory acceptance at AMOS SA, the telescope has been dismounted, packed, transported, and re-mounted on site. This paper provides the final performances (i.e. image quality, pointing and tracking) measured during sky tests at Devasthal Observatory.

9906-166, Session PS6

Alignment procedure for the South African Astronomical Observatory's 74-inch (1.9-m) telescope

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A great deal of effort has gone into improving the performance and reliability of the SAAO's 74-inch telescope during the past year. This includes replacing the telescope encoders, refining the pointing model, water-proofing the dome and shutter, replacing the old fibre infrastructure and increasing the telescope throughput – the latter by re-aluminising the primary and correctly aligning the mirrors. The re-aluminising is described in AS103-149 and here we present the procedure developed to ensure the optimal alignment of the telescope mirrors. This technique is based on the process used to align the 107-inch Harlan J. Smith Telescope at McDonald Observatory in West Texas, adapted to suit the SAAO 74-inch. Being an optically slow telescope (F/18 at the Cassegrain focus), the alignment of the 74-inch is insensitive to translation, only tip/tilt adjustment of the two mirrors is required. The equipment list includes a Taylor Hobson Micro Alignment Telescope (AT) and a custom-built mount employing high precision adjusters to provide the necessary X-Y and tip/tilt adjustment of the AT. This mount securely attaches the AT to the Cassegrain port on the 74-inch instrument rotator, allowing the AT to be rotated back and forth on the telescope's tail-piece while pointing up at the secondary mirror through the Cassegrain hole. A set of crosswires is arbitrarily set up atop the central baffle in the primary mirror, and a piece of graph paper is secured in front of the secondary mirror. With the AT focused on the crosswire, the tail-piece of the telescope is rotated back and forth through 180 degrees and the crosswire adjusted (iteratively) until the crosswire no longer describes an arc in the AT as the tail-piece rotates. This process is repeated with the graph paper and so the crosswire and graph paper become the near and far references that mark the rotation axis of the instrument rotator. We define this rotation axis to be the optical axis of the telescope, since the instruments attach to the tail-piece and this is what counts. Once that axis is defined by the two points in space (viewable individually at the appropriate AT focus settings), the AT has to be translated and adjusted in tip/tilt to place it on the optical axis of the telescope. A custom-made pinhole, illuminated by a bright LED, is centred on the AT axis and this bright pip gets reflected back towards the AT by the secondary mirror. Viewing the return spot in the AT allows the secondary to be adjusted in tip/tilt to bring it into auto-collimation with the AT. With the secondary thus aligned, the AT, crosswire and graph paper can be removed and an eyepiece (or wavefront camera) installed at the Cassegrain port. Comatic star images indicate the need to tip/tilt the primary mirror to align it to the secondary. Tuning out a brightness gradient seen in an out-of-focus image of a bright star may also be used as feedback when adjusting the tip/tilt of the primary mirror to null coma.

9906-167, Session PS6

HET wide-field upgrade tracker system performance

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To enable the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX), a major upgrade to the HET spherical aberration corrector and tracker was implemented to increase the pupil size from 9.2 to 10 meters and the field of view from 4 to 22 arcminutes. The new Tracker, is comprised of 13 servo-controlled axes, weighs 20 tons, and is required to position the corrector to acquire and track targets within the specified +/-9.5um de-center, +/-15um de-focus, and +/-4.4 arc-sec tip/tilt. Following preliminary testing of the Wide Field Upgrade (WFU) Tracker, the Wide Field Corrector (WFC) was installed in July of 2015. This paper describes the physical characteristics of the 115 ton telescope system, metrology techniques utilized, as well as the mount modeling approach and implementation for achieving this requirement, prior to the installation of the corrector. It then follows up with subsequent pointing, acquisition, and tracking tests which were performed after corrector installation, to verify system mechanical, control, and software performance.

9906-168, Session PS6

Verification of alignment status and image quality of KMTNet 1.6m wide-field optical telescopes

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Korea Astronomy and Space Science Institute(KASI) have initiated KMTNet program to discover Earth-mass exoplanets in the habitable zone by analyzing a perturbation signal of micro-lensed light curves. To perform the science KMTNet deployed three identical 1.6-m wide field telescopes equipped with 18k ? 18k Mosaic CCD camera covering 2?2deg? FOV in the Southern hemisphere. Since the planetary signal is so weak to be distinguished from the amplified noisy light curves, it is critical to maintain the performance of the three telescopes as best and consistent alignment status. To accommodate highly demanding periodic verification of the alignment status of the telescopes, an interferometric wavefront test using a CGH has been implemented. This paper presents overview of the telescopes, flow down of error budget, actual alignment process and results from the alignment verification by system wavefront test. Also the measured on-sky image quality has been evaluated and reviewed along with the telescope alignment status.

9906-169, Session PS6

Supernova and optical transient observations using the three wide-field telescope array of the KMTNet

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The Korean Microlensing Telescope Network (KMTNet) is a network of three new 1.6-m, wide-field telescopes spread over three different sites in Chile, South Africa and Australia. Each telescope is equipped with a wide-field, i.e., 2 degree by 2 degree, CCD camera of 18K by 18K detector pixels of four mosaic CCDs from E2V. The pixel sampling of the CCD camera is 0.4" and BVRI and H-alpha filters are available. These make the KMTNet facility an ideal and unique facility for discovering and monitoring supernovae and other optical transients by providing continuous 24-hour sky coverage of the 4 square degree wide field. The KMTNet supernova program (KSP), which we report here, is a program that uses approximately 20% of the entire KMTNet observing time in 2015-2019 for observations of supernovae alongside other optical transients and related sources. The program is exclusively focused on discovering early supernovae and peculiar ones by conducting high-cadence, multi-color monitoring observations - we typically visit a smaller number of nearby galaxies several times per night using three different filters of B, V and I, aiming primarily at detecting early supernovae within a few hours from the explosion and obtaining their useful color information for detailed photometric analyses. We use a combination of publicly-available algorithms and our own programs for the data processing and analyses. These comprise routines for image re-projection, source detection, image combination and subtraction, false alarm, automatic photometry and light curve extraction, etc. Our early results include the detection of a highly eccentric optical transient that shows a previously-unidentified light curve to the best of our knowledge, a candidate for early supernova potentially detected within only several minutes from the explosion, various types of variable stars of long and short periods, numerous low surface brightness dwarf galaxies and tidal streams.

9906-170, Session PS6

Comparison of LSST and DECam wavefront recovery algorithms

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We make a detailed quantitative comparison of the wavefront recovery algorithms developed for DECam and LSST. Samples used in this study includes images of out of focus stars collected by the Dark Energy Camera at the Blanco 4-meter and artificial donuts simulated from a Kolmogorov model of the atmosphere and an optical model of LSST. Both samples are analyzed with the forward wavefront retrieval algorithm developed for DECam and the transport of intensity algorithm developed for LSST. Quantitative comparison of results between the two implemented algorithms is made, and the relative strengths and weaknesses of each algorithms is discussed.

9906-171, Session PS6

Long-term performance of the VLT UT active optics system

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For telescopes with large and thin solid meniscus mirrors, like the Very Large Telescopes (VLT) unit telescopes (UT), it is compulsory to use an effective and reliable active optics system in order to guarantee the optimal optical performance. The actual performance of a telescope depends strongly on the avoidance of wavefront aberrations. The main error sources, ordered according to the average frequency of their band-pass, are optical design and manufacturing, structural deformations, support errors, local air and the free atmosphere. By definition, active optics corrects only slowly varying errors generated by the telescope itself and, partially, by air effects near the telescope. The frequency limit for the active optics system is 0.03 Hz. Systems that deal with higher frequency aberrations are called adaptive optics systems and are not considered in this paper. The VLT active optics system runs in closed loop operation, using a Shack-Hartmann sensor for wavefront analysis and performing the corrections on the primary and secondary mirror. Movements of the secondary mirror correct defocus and decentering coma, while all other wavefront errors are corrected by changing the shape of the primary mirror, using differential force changes. The active optics system of the VLT is now continuously in operation since 1998. In order to evaluate the long-term performance of the system, an extended timeseries data analysis of the available telemetry data for all unit telescopes was performed. The dependence of the system performance on external (e.g. seeing, wind speed and ambient temperature) and internal parameters (e.g. performance of Shack-Hartmann wavefront analyzer, the used algorithms for wavefront reconstruction and telescope altitude position) is analyzed in order to give a detailed performance estimate for the different unit telescopes. To assed the basic performance of the system, the residual RMS wavefront error is used as performance indicator. The RMS error is the expected error after application of the forces that correct the last fitting. Assuming the force application to be perfect then this corresponds directly to the optical performance of the system. The results presented in this paper demonstrate that the VLT UT active optics system works very stable and reliable with no performance degradation over time.

9906-172, Session PS6

Telescope performance at the Large Binocular Telescope

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The Large Binocular Telescope Observatory is a collaboration between institutions in Arizona, Germany, Italy, Indiana, Minnesota, Ohio and Virginia. The telescope uses two 8.4-m diameter primary mirrors mounted side-by-side on the same AZ-EL mount to produce a collecting area equivalent to an 11.8-meter aperture. Adaptive optics loops are routinely closed with natural stars on both sides for sided and combined beam observations. Rayleigh laser guide stars provide GLAO seeing improvement. With the telescope now in operation for 10 years, we report on various statistics of telescope performance and seeing-limited image quality. Performance of the adaptive optics systems and instruments are discussed elsewhere. Statistics of telescope performance are reported in the areas of off-axis guiding, active optics, and open-loop mount tracking. Delivered image quality is reported as measured by the DIMM and several guide cameras as a function of other parameters such as temperature, wind velocity and wind direction. The performance of the honeycomb mirror ventilation

system is also discussed as it impacts local seeing and collimation. Projects to improve image quality and dome seeing are underway.

9906-31, Session 9

The E-ELT program status *(Invited Paper)*

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The European Extremely Large Telescope (E-ELT) is a 39m optical/infrared telescope to be located on Cerro Armazones about 25 km away from the current ESO VLT Observatory at Cerro Paranal, Chile. After initial conceptual studies in collaboration with the community and preliminary design studies performed with industrial partners, the Programme was formally approved in 2012 with the requirement that major spending should be initiated only when the funding level would reach 90% of the total cost to completion. This was expected to be reached soon when Brazil would formally join ESO as a new Member State. However, the accession procedure of Brazil taking more time than originally anticipated, ESO Council decided in December 2014 to give the green-light for the construction of a first phase (Phase 1) that could defer the development of some components while preserving the future science capabilities and synergy with other project such as the James Web Space Telescope. This ‘green light' marked the start of an intense effort on many fronts, within ESO and inside the member states astronomical community, to launch the required construction activities.

This paper will first recall the main scientific objectives of the E-ELT and describe the interaction with the scientific community and ESO's committees that recently led to the signature of the agreements with consortia of astronomical institutes for the development of the first set of three instruments. An overview of the management organization will be provided, highlighting the challenges inherent to such large telescope projects but also related to the phased approach imposed by the funding situation.

The overall status of the project will then be described focusing on the major achievements obtained since early 2015.

These include the completion of the 24km road and the top platform at Cerro Armazones which is the result of a contract signed with the Chilean company ICAFAL back in late 2013 and completed in fall 2015.

Another significant achievement, in early summer 2015, was the signature of two industrial contracts for the production of the highly fragile thin shells of the 2.5m diameter M4 adaptive mirror as well as the final design and construction of the complete M4 Unit. Those are the first contracts to deliver hardware that will eventually equip the telescope.

The managerial and system engineering processes put in place to support the launch and the follow-up of such construction contracts will be briefly described.

Later in 2015, the joined effort by ESO and the scientific community in ESO member states led to the signature of the agreements for the design and construction of the first set of instruments: a precision wide-field, high-resolution (Adaptive Optics) imager (MICADO), an integral field spectrograph (HARMONI) and a thermal-infrared imager and spectrometer (METIS) as well as a multi-conjugate adaptive optics module using 6 laser guide stars (MAORY).

In addition, the article will report on the result of currently on-going activities such as the call for tender for the most important contract in the E-ELT Programme and in ESO history, namely for the Dome and the Main Structure and the procurement of the opto-mechanics.

The main processes and tools put in place to manage and control the Programme complexity will be briefly presented as well as its master schedule.

9906-32, Session 9

E-ELT assembly, integration, and technical commissioning plans

Peter Gray, Emanuela Ciattaglia, F. Gago, S. Guisard, Juan Marrero, Robert Ridings, Andrew Wright, European Southern Observatory (Germany)

EELT AIV is the activity of assembly, integration and technical commissioning of EELT sub-systems to deliver an operational telescope and the first light instrument technically capable of the top-level requirements and ready to start science commissioning leading to operations. The AIV phase covers all technical activities on Armazones from the moment the sub-systems and components are delivered or accepted on-site (by the sub-system EELT project manager). AIV includes final system tests of the completed telescope (known as “Technical Commissioning”) and the installation, alignment and telescope integration of the science instruments. The AIV phase ends with the handover of the completed telescope with installed instruments to the start of Science Commissioning. Responsibility then passes to the Commissioning team, however the technical resources for debugging and tuning the telescope and instrument will come from a combination of the AIV team working together with the Paranal operations staff. AIV is the major technical challenge of EELT. The scale and complexity of the telescope involves challenging logistical and scheduling i.e. 798 mirror segments, staged delivery over 4 years, 5,000 edge sensor pairs, 2,376 position actuators. More than ten major sub-systems e.g.M2-3-4-5, PFS & instruments will be integrated and tested in parallel. Finally, the technical commissioning phase will be a significant challenge. EELT is a highly complex active telescope system. During early testing nothing will be straightforward and there will be many system-level problems to overcome.It will take the “best of the best” people to troubleshoot, debug, tune, and turn over as an operational facility.

9906-33, Session 9

Overview of key technologies for TMT telescope structure

Yutaka Ezaki, Noboru Kawaguchi, Junji Takaki, Atsushi Kato, Tomoya Hattori, Toshitaka Nakaoji, Yusuke Saruta, Satoru Sofuku, Masaki Tabata, Yoshihiro Hosokawa, Mitsubishi Electric Corp. (Japan)

Mitsubishi Electric Corporation has been in charge of many telescopes such as Subaru 8.2 meter optical telescope and ALMA 16 radio telescopes.

In the TMT project, Mitsubishi Electric Corporation is advancing the detailed design of the following systems.

- Telescope structure that exceeds 50 meter in width, height and 2,000 ton in weight
- Telescope drive control systems
- Segment exchange system

For these systems, technical requirements below are specified, to which technical challenges are needed.

- The telescope structure that is light-weight but has small gravitational deformation of the primary mirror cell during elevation angle change
- The telescope structure with seismic isolation system that withstand large earthquake of 1000 thousand year return period
- Drive control of massive telescope structure that realizes high tracking accuracy and short move performance
- Segment exchange system that enables 10 segment exchanges per day.

To satisfy these technical requirements, Mitsubishi Electric Corporation has conducted the detail design and the technology developments. In this paper, the major key technologies that are planned to be applied in the detailed design phase are introduced.

9906-34, Session 9

Production metrology design and calibration for TMT primary mirror fabrication used at multiple manufacturing sites

Ulrich Mueller, Integrated Optical Systems (United States)

The TMT telescope is being built by several partnering countries. Each of them produces a share of the 492 mirror segments consisting of 82 different segment types. In order to produce consistent results at each site the metrology has to be cross calibrated and the segment surface data has to be traceable from raw glass blank through grinding, polishing and hexing into a segment.

An automated metrology instrument called 2-D profilometer (2DP) was designed. Each site uses a copy of this instrument for roundel fabrication, post hexing metrology and alignment of the hex segment in the telescopes SSA assemblies. The error budget for this design will be presented and compared to actual test results.

The 2DP uses 61 surface probes mounted in a carbon fiber panel (CFRP) to measure the surface shape of the mirrors. The panel is attached to a rotary actuator that positions it at any desired angle on the part to be measured. It can be lowered from the rotary axis to the mirror surface using 3 steel wires. During measurement when the CFRP touches the mirror surface with three balls. In order to reduce the weight deformation of the surface and minimize hertzian contact stress under the contact points the CFRP is counterweighted at the three contact points. The surface probes are arranged in a spiral manner such that each probe evaluates the same amount of surface area. The system capability to measure the surface at multiple angles. This leads to dense surface data. In order to align the data with the segment coordinate system cameras measure the position of backside fiducials on the part.

The fiducials are applied at each segment backside to report surface data orientation throughout the manufacturing and assembly process. The fiducials are applied using a carbon fiber fixture that uses replaceable sandblast masks. The location of the fiducials were calibrated using a coordinate measurement machine (CMM) calibration using an optical probe.

Two 1.5diameter Reference Spheres were built with the median radius of the primary mirror segments. There surface were evaluated for radius and figure at their respective polishing sites. These spheres are the metrology null at the Japan, USA and India manufacturing site. The 2DP is nulled on the sphere prior to each measurement. Both spheres and their mounts were shipped to the Coherent, Richmond site for cross calibration. After the 2DP instruments were completed the repeatability and reproducibility was evaluated using repeat measurements on the reference spheres. The two reference spheres were compared using each 2DP to verify the optical and CMM data provided by the manufacturer. In addition a self-calibration scheme proposed by Jerry Nelson was used measure the non-axisymmetric terms of the surface figure. The angles used during this calibration are selected based on the sensitivity of the non-axisymmetric terms vs the angle. This fast process can be used intermittently during manufacturing to verify that the instrument is still working well.

9906-35, Session 9

GMT site, enclosure, and facilities design and development overview and update

Jose Teran, M3 Engineering & Technology Corp. (United States); William S. Burgett, GMTO Corp. (United States); Eric Grigel, M3 Engineering & Technology Corp. (United States); Bruce C. Bigelow, Eduardo Donoso, GMTO Corp. (United States); Fransisco Figueroa, GMTO Corp. (Chile)

The Giant Magellan Telescope (GMT) will have a 25.4-meter diameter effective aperture, and is one of three currently planned next generation extremely large telescopes (ELTs). The GMT will be located at the summit of Cerro Campanas at the Las Campanas Observatory (LCO) in Chile, one of the world's best observing sites.

This paper provides an overview of the site master plan comprising site infrastructure, enclosure, and facilities, and outlines the analysis of alternatives trade studies that will lead to the final design. Also presented is an update of the site infrastructure development and pre-construction activities currently underway that will be completed prior to the beginning of enclosure construction near the end of 2016.

9906-36, Session 10

Primary mirror control for large segmented telescopes: combining high performance with robustness

Gert Witvoet, TNO (Netherlands); Niek Doelman, TNO (Netherlands) and Leiden Observatory (Netherlands); Remco den Breeje, TNO (Netherlands)

The desire for improved resolution has led to the design of increasingly larger telescopes, such as the Thirty Meter Telescope (TMT) and the European Extremely Large Telescope (E-ELT). Their enormous sizes require them to use a segmented primary mirror concept. Each individual mirror segment must then be actively controlled, e.g. in rigid-body piston, tip and tilt motions, in order to create the desired mirror surface shape, even in the presence of disturbances. To this end each segment needs to be equipped with three dedicated single-DOF actuators. These piston-tip-tilt actuators should combine extremely high accuracy with a relatively large stroke (to compensate for the rotation with respect to the gravitational field), while being exposed to non-stationary structural vibrations and wind loads.

In the E-ELT case there will be a total of 2394 piston-tip-tilt actuators, each of them actively controlled. Each actuator will experience a different structural dynamical response, which could even change with the orientation of the telescope, since the actuator—segment assemblies on e.g. the edge of the primary mirror will behave differently from the ones in the center. The same holds for the disturbances; wind forces and frame vibrations on the edge will be different than in the center. When using classical control strategies, this imposes a dilemma. Designing one robust controller for all actuators will inevitably sacrifice performance, while designing 2394 different controllers for all possible disturbances will be extremely cumbersome or even infeasible.

To overcome this classical trade-off between robustness and performance, TNO has developed and tested an automated control strategy for mirror segment actuators. The goal of this development was to create one single reliable algorithm which can be applied to all actuators (thus being robust to variations in dynamics), automatically tunes itself to obtain optimal performance, and tracks the disturbances over time, thereby maintaining its optimality. The basis is a very robust (but low-performant) linear feedback loop, which is automatically identified within a few seconds. The identified closed-loop system is then used both in a real-time estimation of the disturbances, and for the conditioning of an additional adaptive controller. This automated controller converges to optimal performance in less than 10 minutes from the start, and keeps track of changing disturbances. The algorithm has been successfully demonstrated on a segment actuator prototype for the E-ELT, converging to sub-nanometer accuracy, which surpasses earlier results with classic linear controller design. Moreover, the stability and reliability of the algorithm has been demonstrated over multiple days. These tests illustrate the feasibility of such an approach on a segmented telescope like the E-ELT, where in principle all 2394 actuators can be automatically tuned to an optimal

performance within just a couple of minutes after the press on a single button, and kept optimal even when the wind forces or frame vibrations change over time.

9906-37, Session 11

Overview and status of the Giant Magellan Telescope Project *(Invited Paper)*

Patrick J. McCarthy, James L. Fanson, Rebecca A. Bernstein, GMTO Corp. (United States)

We will report on the status of the Giant Magellan Telescope (GMT) Project. The GMT is a 25m telescope built around seven 8.4m honeycomb primary mirrors and a segmented secondary mirror system. The telescope is designed to address forefront questions in astrophysics, cosmology and the study of exoplanets. Adaptive optics is integral to the system through the use of adaptive secondary mirrors that share heritage with a number of 8m class telescopes. The GMT will be located at Las Campanas Observatory in Chile. The site has been thoroughly characterized following an extensive site testing campaign and has excellent seeing and weather.

The GMT project has moved to the construction phase following a series of reviews in 2014. Production of the primary mirror segments is progressing with segments 1-4 under contract and long-lead time materials procured for segments 5 and 6. Core infrastructure at the GMT site is nearing completion as power, water, roads and staff housing are under development. Designs for the telescope, enclosure and key subsystems are proceeding from preliminary through final design phases in anticipation of the release of major fabrication contracts in 2016. Several subsystems are undergoing prototype development to reduce risk. Primary mirror supports, positional actuators and thermal control systems have been prototyped and are undergoing testing. A subscale prototype adaptive secondary mirror segment that includes the final electronics and incorporates the geometry of the GMT segmented secondary mirrors is under development. The telescope phasing system has been tested using a segmented pupil on the Baade 6.5m telescope at Las Campanas and meets our capture range and sensitivity requirements.

As one of the three Extremely Large Telescopes under development the GMT is an important part of the next generation of astronomical observatories. Since the 2014 SPIE meeting the GMT project has undergone considerable growth and is now poised to start major construction. We will report on the status of the project as of the first quarter of 2016.

9906-38, Session 11

The GMT active optics system: design and simulated end-to-end performance

Brian McLeod, Harvard-Smithsonian Ctr. for Astrophysics (United States); Antonin H. Bouchez, GMTO Corp. (United States); Daniel Catropa, Harvard-Smithsonian Ctr. for Astrophysics (United States); Rodolphe Conan, Alan Conder, Benjamin Irarrazaval, GMTO Corp. (United States); Derek Kopon, Kenneth McCracken, Stuart McMuldroch, William A. Podgorski, Harvard-Smithsonian Ctr. for Astrophysics (United States); Fernando Quirós-Pacheco, GMTO Corp. (United States)

The alignment and figure control of the seven 8.5-m primary and seven 1-m secondary mirror segments of the Giant Magellan Telescope will be controlled by the active optics system. We consider the performance of the telescope under the influence of perturbations including wind-shake, vibration, atmospheric turbulence, and gravity- and thermal-induced distortions of the structure and optics. The measurements driving the control system are made using a set of four off-axis Shack-Hartmann sensors that comprise the Acquisition Guiding and Wavefront-sensing System. We present end-to-end simulations including the perturbations, optical propagation, sensors, and the control algorithms.

9906-41, Session 11

Designing the primary mirror support for the E-ELT

Jan Nijenhuis, TNO (Netherlands)

During the period 2009-2010 prototypes for the primary mirror support of the E-ELT have been developed. These have been tested elaborately by ESO. Design improvement were found to be necessary, especially in the field of manufacturability and maintainability. Furthermore, the technical performance had to improve in specific areas as well. This has evolved into a new specifications which have resulted in a new design for the segment support structure. The design rules that have led to the prototype design have been maintained but the implementation has been much improved. Also considerable improvement has been obtained with respect to the dynamic behavior. Accessibility and visibility on all parts and subsystems has changed such that everything is clearly visible now. Despite the increased performance no mass increase has been recorded meaning that more efficient use has been made of the material.

The active means to influence the segment shape by use of the warping harness has been completely redesigned. Cooperation between the TNO team and TMT has led to a design that has much in common but is also optimized for the specific performance requirements of the individual telescopes. A very important quality that has been achieved is simplicity. Hence a minimum amount of components is used. Reliability and safety were other aspects that have been greatly improved compared to the prototypes.

9906-42, Session 11

Thirty Meter Telescope project status *(Invited Paper)*

Fengchuan Li, Gary H. Sanders, Thirty Meter Telescope (United States) and California Institute of Technology (United States)

The Thirty Meter Telescope (TMT) is an extremely large optical-infrared telescope with diffraction-limited performance that will shape the landscape of astronomy for the next 50 years from its vantage point in the northern hemisphere on Mauna Kea, Hawaii, USA. The TMT International Observatory is a public-private-international partnership that unites the scientific, instrumental and industrial communities of India, Canada, China, Japan and the USA for this endeavor with all partners contributing to the design, development, and scientific use of the observatory. This paper will describe progress made since the construction phase started in April, 2014: challenges and opportunities on the telescope site, communications and management of a truly global collaboration, requirements flow down and interface definition, telescope and instrument performance, hardware and software development, education and public outreach.

9906-112, Session 11

A 3D metrology system for the Giant Magellan Telescope

Andrew P. Rakich, Lee R. Dettmann, Wylie N. Rosenthal, Chris Alongi, GMTO Corp. (United States)

The Giant Magellan Telescope (GMT) will consist of seven 8.4 m aperture telescopes mounted as a radially symmetrical phased array in a common mount. Each primary and conjugated secondary mirror segment will optically feed a common instrument interface. During telescope operation, it is expected that the alignment of the optical components will deflect due to nonrepeatable variations in thermal environment and gravity induced structural flexure of the mount. In order to reposition the optical components due to these influences, a metrology system incorporating a large number of absolute distance measuring interferometers is being developed for the GMT. The system would be required to align optical components of the telescope to the instrument interface to within the capture range of the active optics wavefront sensing systems. Combinations of multiple interferometric measurement paths would provide information to the telescope actuator control system to maintain the rigid body orientation between the primary and secondary mirror segments, as well as between the central primary mirror segment and the reference instrument interface. The interferometers and targets would be mounted directly to the optical components to minimize differential deflection between the optical surface and the metrology network. Since the interferometers measure the absolute distance to an optical target, the system could be shuttered or powered off while telescope science data is being acquired and collimation is maintained using information from the wavefront sensing systems. Initial investigations of the Absolute Multiline™ system by Etalon AG show that a metrology network based on this product should be capable of meeting all of the requirements. This system uses a large number of optical fibers to illuminate individual distance measuring interferometers. The individual components that would be mounted to the optical elements are passive and relatively inexpensive. A series of measurements using this product have been made to evaluate the performance of the system in conditions that are similar to the environment at the telescope site. A subscale geometry test has also been performed and results are compared to displacements measured with laser tracker and coordinate measurement machine, (CMM). A conceptual design of the system is presented and expected performance based on simulations is discussed.

9906-251, Session 11

Iranian National Observatory; project overview

Habib Khosroshahi, Iranian National Observatory (Iran, Islamic Republic of)

No Abstract Available

9906-43, Session 12

Very high energy gamma-ray astronomy with the Cherenkov Telescope Array

(Invited Paper)

Werner Hofmann, CTA Consortium (Germany) and Max-Planck-Institut für Kernphysik (Germany)

Very high energy gamma-ray astronomy – with energies in the teraelectronvolt domain– has made rapid strides in the last decade, driven mainly by the atmospheric Cherenkov technique, where gamma-ray induced particle cascades in the atmosphere are imaged with large telescopes. The first VHE source was discovered in 1989; currently the number of known sources is approaching 200, tracing cosmic particle accelerators.

The Cherenkov Telescope Array (CTA) is a next-generation observatory for very high energy (VHE) gamma-ray astronomy, supported by a worldwide community. With one array of imaging atmospheric Cherenkov telescopes each in the northern and southern hemispheres, CTA will provide full-sky coverage, enhance flux sensitivity by one order of magnitude compared to current instruments, and cover a four-decade energy range.

The presentation will aim at covering the science drivers, function, design characteristics, and status of CTA.

9906-44, Session 12

The ASTRI SST-2M prototype for the Cherenkov Telescope Array: opto-mechanical performance

Rodolfo Canestrari, INAF - Osservatorio Astronomico di Brera (Italy); Enrico Giro, INAF - Osservatorio Astronomico di Padova (Italy); Salvatore Scuderi, INAF - Osservatorio Astrofisico di Catania (Italy); Gino Tosti, Elisa Antolini, Univ. degli Studi di Perugia (Italy); Giorgia Sironi, Claudio Tanci, Dino Fugazza, INAF - Osservatorio Astronomico di Brera (Italy); Federico Russo, INAF - Osservatorio Astrofisico di Torino (Italy); Daniele Gardiol, INAF - Osservatorio Astronomico di Torino (Italy); Carlos Eduardo Fermino, USP (Brazil); Luca Stringhetti, INAF - IASF Milano (Italy); Giovanni Pareschi, INAF - Osservatorio Astronomico di Brera (Italy)

ASTRI SST-2M is an end-to-end telescope prototype developed by the Italian National Institute of Astrophysics (INAF) in the framework of the Cherenkov Telescope Array (CTA). The CTA observatory, with a combination of large-, medium-, and small-size telescopes (LST, MST and SST, respectively), will represent the next generation of imaging atmospheric Cherenkov telescopes. It will explore the very high-energy domain from a few tens of GeV up to few hundreds of TeV.

The ASTRI SST-2M telescope structure and mirrors have been installed at the INAF observing station at Serra La Nave, on Mt. Etna (Sicily, Italy) in September 2014. Its performance verification phase began in autumn 2015. Part of the scheduled activities foresees the study and characterization of the optical and opto-mechanical performance of the telescope prototype.

In this contribution we report the results achieved in terms of kinematic model verification, Point Spread Function on the full field of view, and its stability with respect to telescope elevation, the pointing models and effective area.

9906-45, Session 12

FACT: status and experience from four years of operation of the first G-APD Cherenkov Telescope

Adrian Biland, ETH Zürich (Switzerland)

Imaging Atmospheric Cherenkov Telescopes (IACT) are measuring the dim and short flashes of Cherenkov light emitted by extended air showers induced by energetic particles entering the atmosphere. To be able to catch such signals, due to the high background of ambient light even during dark nights, IACT cameras need very sensitive photosensors and fast readout electronics. To be able to statistically distinguish between air showers induced by charged particles and gamma-rays, respectively, the cameras need more than 1000 individual pixels. The current IACT arrays H.E.S.S., MAGIC and VERITAS have proven that the high energy sky is far more diverse than expected, and the next generation CTA is currently in the prototyping phase. So far, all IACTs used Photo Multiplier Tubes (PMT) as photo sensors. When the first generation of Geiger-mode operated Avalanche Photo Diodes (G-APD), nowadays usually called Silicon Photo Multipliers (SiPM), became commercially available, the question raised if these novel devices are a viable alternative to PMTs

under the harsh operation conditions intrinsic to IACTs. The First G-APD Cherenkov Collaboration (FACT) was formed by ETH Zurich and the Universities Geneva, Dortmund and Wuerzburg in 2008, with the intention to develop and install a G-APD based camera in a refurbished 9.5m^2 HEGRA telescope on the Canary island La Palma. In October 2011, the camera having 1440 Pixels, consisting each of a light guide, a G-APD chip with 3600 individual cells and a fast readout electronics operating at 2 Gigasamples per second was installed. Few hours after installation, the camera successfully recorded the first self-triggered Cherenkov images. These first events had been measured under strong moonlight condition that would have damaged standard PMTs if directly exposed to such bright light under full voltage. This already showed one advantage of SiPM.

Within short time, stable operation of was reached, and FACT is taken data almost every night without any major problem encountered so far. To reduce operation cost and load on the members of the small collaboration, FACT is operated since Summer 2012 from remote without the need of a data-taking crew onsite every night. In case of an emergency, it is agreed that the crew of the nearby MAGIC telescopes can be asked for help. Due to the excellent reliability if FACT, the task of operation changed gradually from remote operation to remote system monitoring, and fully robotic operation is envisaged.

The success of FACT convinced the community, and several SiPM based projects for CTA exist now. In addition to investigating the viability of SiPM, FACT is regularly monitoring the high-energy emission of several bright extra-galactic sources and alerting the community in case of bright flaring activities. This observations also allow to gain long term experience about the performance of SiPM. Despite regular operation under bright moonlight conditions and therefore collecting far more photons per sensor than under dark night observations, no indication of any ageing or any other SiPM related problem was encountered so far.

9906-46, Session 13

Construction status of the Daniel K. Inouye Solar Telescope *(Invited Paper)*

Joseph P. McMullin, Thomas R. Rimmele, Mark Warner, Valentin Martinez Pillet, National Solar Observatory (United States); Roberto Casini, National Ctr. for Atmospheric Research (United States); Steven J. Berukoff, Simon C. Craig, David F. Elmore, Andrew Ferayorni, Robert P. Hubbard, Bret D. Goodrich, David Harrington, Steve L. Hegwer, Paul Jeffers, Erik M. Johansson, National Solar Observatory (United States); Jeffrey R. Kuhn, Haosheng Lin, Univ. of Hawai'i (United States); Heather K. Marshall, National Solar Observatory (United States); Mihalis Mathioudakis, Queen's Univ. Belfast (United Kingdom); William R. McBride II, William McVeigh, National Solar Observatory (United States); Wolfgang Schmidt, Kiepenheuer-Institut für Sonnenphysik (Germany); Steve Shimko, Stacey R. Sueoka, Alexandra Tritschler, Timothy R. Williams, Friedrich Wöger, National Solar Observatory (United States)

We provide an update on the construction status of the Daniel K. Inouye Solar Telescope (renamed from the ATST, Advanced Technology Solar Telescope, in December 2013). This 4-m diameter facility is designed to enable detection and spatial/temporal resolution of the predicted, fundamental astrophysical processes driving solar magnetism at their intrinsic scales throughout the solar atmosphere. These data will drive key research on solar magnetism and its influence on solar winds, flares, coronal mass ejections and solar irradiance variability. The facility is developed to support a broad wavelength range (0.35 to 28 microns) and will employ state-of-the-art adaptive optics systems to provide diffraction limited imaging, resolving features approximately 20 km on the Sun. At the start of operations, there will be five instruments initially deployed: Visible Broadband Imager (VBI; National Solar Observatory), Visible SpectroPolarimeter (ViSP; NCAR High Altitude Observatory), Visible Tunable Filter (VTF (a Fabry-Perot tunable spectropolarimeter); Kiepenheuer Institute for Solarphysics), Diffraction Limited NIR Spectropolarimeter (DL-NIRSP; University of Hawaii, Institute for Astronomy) and the Cryogenic NIR Spectropolarimeter (Cryo-NIRSP; University of Hawaii, Institute for Astronomy).

As of mid-2016, the project construction is in its 4th year of site construction and 7th year overall.

Major milestones in the off-site development include the conclusion of the polishing of the M1 mirror by University of Arizona, College of Optical Sciences, the delivery of the Top End Optical Assembly (L3), the acceptance of the Deformable Mirror System (Xinetics); all optical systems have been contracted and are either accepted or in fabrication.

The Enclosure and Telescope Mount Assembly passed through their factory acceptance in 2014 and 2015, respectively. The enclosure site construction is currently concluding while the Telescope Mount Assembly site erection is underway. The facility buildings (Utility and Support and Operations) have been completed with ongoing work on the thermal systems to support the challenging imaging requirements needed for the solar research. The instrument systems have mostly completed their critical design reviews and are in fabrication.

Finally, we present the plans for the integration and commissioning leading to a start of operations in late 2019 as well as the ongoing risk management.

9906-48, Session 13

Integration of functional safety systems on the Daniel K. Inouye Solar Telescope

Timothy R. Williams, Robert P. Hubbard, National Solar Observatory (United States)

The Daniel K. Inouye Solar Telescope (DKIST) was envisioned from an early stage to incorporate a functional safety system to ensure the safety of personnel and equipment within the facility. Early hazard analysis by a dedicated hazard analysis team showed the need for a functional safety system. The design used a distributed approach in which each major subsystem contains a PLC-based safety controller. This PLC-based system complies with the latest international standards for functional safety. During the design phase, the hazard analysis team continued to analyze the design as it was refined. The use of a programmable controller also allows for flexibility to incorporate changes in the design of subsystems without negatively impacting safety.

Various subsystems were built by different contractors and project partners but had to function as a piece of the overall control system. Using distributed controllers allows project contractors and partners to build components as standalone subsystems that then need to be integrated into the overall functional safety system. Recently factory testing was concluded on the major subsystems of the facility. Final integration of these subsystems is currently underway on the site. Building on lessons learned in early factory tests, changes to the interface between subsystems were made to improve the speed and ease of integration of the entire system. New safety functions were need as revealed by continuous hazard analysis of the design and requirements.

Because of the distributed design, each subsystem can be brought online as it is delivered and assembled rather than waiting until the entire facility is finished. This enhances safety during the risky period of integration and testing. The DKIST has implemented a functional safety system that has allowed construction of subsystems in geographically diverse locations but that function cohesively once they are integrated into the facility currently under construction.

9906-49, Session 13

DKIST telescope mount factory testing overview and lessons learned

Paul Jeffers, National Solar Observatory (United States); Todd Trieloff, Ingersoll Machines Tools, Inc. (United States); Hans J. Kärcher, Steffen Seubert, MT Mechatronics GmbH (Germany); William R. McBride II, National Solar Observatory (United States)

The Daniel K Inouye Solar Telescope (DKIST) will be the largest solar telescope in the world, and will be able to provide the sharpest views ever taken of the solar surface. The telescope has a 4m aperture primary mirror, however due to the off axis nature of the optical layout, the telescope mount has proportions similar to an 8 metre class telescope.

The Telescope Mount Assembly (TMA) includes both the telescope mount and the 16m diameter laboratory table or Coudé Rotator. The Coudé Rotator supports the full instrument suite of up to 40 tonnes and has full rotation capabilities similar to the Mount Azimuth axis. The TMA has been going through the design, fabrication and assembly process since 2009 with Ingersoll Machine Tool's and this culminated with the Factory Acceptance Testing (FAT).

The preparation for the FAT started not long after the Final Design Review was complete and planning continued through the assembly stages. The official Factory Acceptance testing of the Coudé Rotator was conducted during May/Jun 2014 and the Mount in Jan through Apr 2015.

This paper provides an overview and discussion of the testing that was carried out. The depth and extent of testing will be described with discussion on what we would do differently next time. Also details of the preparation / process that lead into the testing will be presented.

Most importantly the results will be summarized and lessons learned during the testing provided as well as discussion on how this influences the planned site assembly and extent of re-test post assembly.

9906-50, Session 13

New Solar Telescope and its science instruments

Wenda Cao, Philip R. Goode, Big Bear Solar Observatory (United States) and New Jersey Institute of Technology (United States)

The 1.6-meter clear aperture, off-axis New Solar Telescope (NST) is the first facility class solar telescope built in the U.S. for a generation and is largest aperture, highest resolution solar telescope in the world. NST will dominate U.S. ground-based solar observations until the end of this decade when the 4-m DKIST comes online. Since its commissioning in 2009, the NST has regularly provided high resolution data covering the spectral range from 0.4 to 5.0 ?m to photometrically and polarimetrically probe the solar atmosphere from the deepest photosphere to the base of the corona, from the smallest scales to largest scales, and from the quietest to most active Sun. This presentation reports the up-to-date progress on the NST and its next generation instruments including the AO systems (AO-308 & MCAO), the Broad-band Filter Imager (BFI), the Near-InfraRed Imaging Spectro-polarimeter (NIRIS), the Visible Imaging Spectrometer (VIS), and the Cryogenic Infrared Spectrograph (CYRA).

9906-196, Session 13

Active thermal control for the 1.8-m primary mirror of the solar telescope CLST

Yangyi Liu, Naiting Gu, Cheng Li, Yuntao Cheng, Benxi Yao, Zhiyong Wang, Changhui Rao, Institute of Optics and Electronics (China)

The primary mirror of solar telescope is heated by the solar radiation and introduce harmful mirror seeing degrading the imaging quality. In essence, the mirror seeing is produced by the air convection temperature difference between heated primary mirror surface and ambient air. For the 1.8-m Chinese Large Solar Telescope (CLST), the quantitative relationship between the mirror seeing effect, wind velocity and temperature difference between primary mirror surface and ambient air under different convection type is established. The analytical results show that the maximum temperature rise is within 1 kelvin under the condition that the corresponding image degradation induced by the mirror seeing effect is less than 0.05 arc seconds, which is the maximum optical tolerance for mirror seeing effect based on the optical tolerance distribution for the CLST. To meet this thermal requirement, an active thermal control system and its control strategy design based on the concept of "temperature compensation" for the CLST primary mirror is proposed. The thermal control system includes two subsystems: one is the cooling subsystem and the other is the heating subsystem. On the one hand, when the primary mirror surface temperature is higher than the ambient air, the cooling subsystem works and cools the primary mirror surface. On the other hand, when the primary mirror surface temperature is lower than the ambient air, the heating subsystem works and heats the primary mirror surface. Therefore, the temperature difference induced by the variable solar irradiance and fluctuating ambient air temperature is rapidly eliminated under the collaborative work of above two subsystems. The corresponding numerical simulation validates the thermal control system. Furthermore, the outfield experiment has also been carried out to validate its effectiveness. Based on the experimental system, the thermal control system is able to control the temperature difference between primary mirror surface and ambient air within 1 Kelvin during one day's continuous solar irradiance. In the meanwhile, the average and maximum temperature difference between primary mirror surface and ambient air are less than 0.3 and 0.7 Kelvins respectively. It completely meets the proposed thermal requirement. The relevant thermal control design has already been used in the CLST.

9906-52, Session 14

Investigation of effects on figure of W. M. Keck Observatory primary mirror segments due to installation of new supports

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The W. M. Keck Observatory Segment Repair Project includes replacement of the original axial and radial supports with new designs, and installation of the new supports in different positions. In this paper, we present finite element analyses of a primary mirror segment including whiffletree mirror support system to determine the effect of the modified supports on the mirror figure. Displacements of the front surface are calculated for a number of operational and assembly fit-up cases, and differential displacements between the old and new support system are found. Zernike coefficients are calculated for front surface displacements and differential

displacements. Stresses on the glass surface at the radial pad bond locations are also determined. We find the residual deformations of the mirror front surface with the new supports to be similar to those with the old supports, differing only in the immediate vicinity of the inserts, and the impact on the imaging quality of the Keck telescopes to be negligible.

9906-53, Session 14

Concept design for seismic upgrade of Keck telescopes

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On 15 October 2006 a large earthquake damaged both telescopes at W. M. Keck Observatory resulting in weeks of observing downtime. A significant portion of the downtime was attributed to recovery efforts repairing damage to telescope bearing journals, radial pad support structures, and encoder subsystems. The study uses the finite element models of the telescopes we developed in 2012 and which were reported 2014 SPIE Ground-Based and Airborne Telescope Conference. In this paper, we discuss the conceptual design for the seismic upgrade of the twin Keck Telescopes, and the approach we took to develop the concept. The paper covers the design requirements and constraints for the seismic upgrade, the evaluation method used to check the safety of sensitive components, and the trade-off study used to compare different options and to select the best design. Various design options such as base isolating the structure, strengthening seismic restraints, adding dampers, adding break-away mechanisms, and combinations of these design options are considered in this study. Nonlinear time history analyses are performed to evaluate the performance of the design concepts.

9906-54, Session 14

Mauna Kea Spectroscopic Explorer: the status and progress of a major site redevelopment project

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The Maunakea Spectroscopic Explorer (MSE) project is a collaboration designing the largest non-ELT optical/NIR astronomical telescope. MSE is unique as a major astronomical facility being the only redevelopment of an existing site, that of CFHT, with a newly expanded partnership. The project office is hosted at the Canada France Hawaii Telescope in Waimea HI, and includes new partners from Australia, China, India and Spain. The project is being developed by an international collaboration with design team membership distributed across three continents. In addition to a report on the progress and organization of design work, this paper will describe the challenges of redeveloping a major astronomical site. We will discuss the Project Office and engineering work from the aspects of meeting the Science requirements while satisfying the unique conditions imposed by redevelopment on Maunakea.

9906-55, Session 14

The large arrays- from ALMA to SKA and CTA: meeting the specifications for successful productions

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2015 sees the completion of the ALMA European Antennas Warranty Period: more than 10 years of System Engineering.

25 (12m diameter) out of the 66 antennas constituting the ALMA Array, have been delivered by AEM consortium composed by Thales Alenia Space France, Thales Alenia Space Italy , European Industrial Engineering (EIE GROUP), and MT Mechatronics.

Other two big astronomical instruments arrays are now passing from the conceptual phase to prototyping and production ones:

SKA (Square Kilometer Array), for which EIE is developing the Dishes and the CTA (Cherenkov Telescope Array) for which EIE is realizing the ASTRI prototypes.

This paper offers a synthesis about the lessons learnt during the development of the ALMA Antennas, presenting all major factors which have been involved, from selection and qualification processes, to management and contractual, engineering and design, prototyping and tests up to the production and installation on site processes.

It is only through well detailed training and focused plans during each phase that success in terms of performances, budget and schedule can be obtained.

The complex phase of requirement definition can lead to the entire project failure if led by inexpert hands.

Inappropriate engineering specifications can result in unsustainable production costs.

Inadequate bidding documentation can lead to inadequate suppliers and products as well as to difficult contractual paths.

Wrong evaluations on the prototyping processes can distort the entire series production phase with unplanned operational and maintenance costs.

This paper is a sort of vademecum by EIE, in more than 25 years experience in the relations with the most important International scientific organizations. A real support for managers and project managers in the astronomical field.

9906-56, Session 14

QUIJOTE-CMB experiment: current status of telescopes and instrumentation

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The QUIJOTE (Q-U-I JOint TEnerife) experiment is an international collaboration led by the Instituto de Astrofísica de Canarias (IAC), with the

participation of The University of Cantabria, The University of Manchester and The University of Cambridge. The installation is located at the Teide Observatory in Tenerife (Canary Islands, Spain).

The main scientific objective of the QUIJOTE Experiment is the characterization of the polarization of the extragalactic emission and the Cosmic Microwave Background (CMB) in the frequency range of 10 – 40 GHz. The instrumentation has been designed with the sensitivity to detect the signature of primordial gravitational-waves generated during the inflationary epoch, if the tensor-to-scalar ratio is larger than r = 0,05.

The whole QUIJOTE project installation consist in a sliding dome building, containing two telescopes of 2,5m and three microwave cryogenic instruments.

The first telescope QT1 and the first instrument MFI (Multi Frequency Instrument) are both operating in the band from 10 to 20 GHz, since November 2012, when the commissioning phase started.

The MFI is a multi-channel instrument with four independent polarimeters to observe at 11, 13, 17 and 19GHz. Its first light occur in November 2012 and scientific routine operation started by May 2013. Nowadays, the instrument works 24 hours per day and 13.330,3h of data have been accumulated, with an observing efficiency (accounting for bad weather and technical maintenance time losses) of about 50%. The main science driver for the MFI is the characterization of the Galactic emission.

The second telescope QT2 and the second instrument TGI (Thirty GHz Instrument) starts working on early 2016, covering the range of 26 to 36 GHz. The second QUIJOTE telescope (QT2) is a replica of QT1, with some improvements in order to amplify capabilities to operate up to 200GHz in the future. This second telescope has been installed and tested at the observatory during 2014, after that, control software has been adapted and commissioned along 2015.

The TGI was conceived to observe exclusively in the 26–36GHz frequency band. The instrument has 30 receivers chains based on a fixed polarizer combined with two phase switches of 90º and 180º working at room temperature and in the direct correlation of the microwave signals. The TGI will be installed in the QT2 focus in January 2016.

Another third instrument, the FGI (Forty GHz Instrument), will join the experiment to complete the sky survey in the frequency range from 37 to 47 GHz. The FGI is based on the same polarimeter concept as the TGI, in fact, the FGI polarimeters will be integrated in the same cryostat than the TGI chains, since the chains are modular in both instruments and the FGI polarimeters fit within the same footprint than the TGI ones. The FGI is composed of 30 polarimetric chains, as well as the TGI, although in this case they are working at 41GHz with 10GHz bandwidth.

Some prototypes of the FGI receivers were built and tested at La Universidad de Cantabria, trying to reduce size, weight and costs, and finally all the elements are being manufactured. Up to day, most of the commercial components have been acquired and fabrication of main subsystem have started. Chains will start to be assembled during the firsts months of 2016 and observing test could be done with some FGI polarimeters by May 2016.

9906-57, Session 15

The Astronomical Telescope of the University of Stuttgart: setup, commissioning, and first results

Karsten Schindler, NASA Ames Research Ctr. (United States) and Deutsches SOFIA Institut (Germany); Jürgen Wolf, NASA Ames Research Ctr. (United States); Giovanni Dal Lago, Gianluca Carotta, Alessio Galliazzo, Officina Stellare SRL (Italy); Alfred Krabbe, Deutsches SOFIA Institut (Germany)

We report about the conceptual design, setup and commissioning of the University of Stuttgart's new 0.6 m telescope, located in the foothills of California's Sierra Nevada. The telescope is operated fully remotely via internet connection since September 2013. Based on extensive optical measurements and a detailed structural analysis, the design of the optical tube assembly has been reiterated considerably. As a result, a Mark II instrument was delivered and setup in May 2015.

The fully-reflective Ritchey-Chrétien telescope features a dual truss structure made of carbon fiber reinforced plastic (CFRP) tubes with titanium alloy joints. The back plane, central frame and front ring are made of a carbon and glass fiber reinforced plastic laminate (CFRP-GFRP-CFRP). Both mirror substrates are manufactured from the ultra-low-expansion glass ceramics CLEARCERAM-Z HS. The primary mirror has a conically shaped backside to reduce its weight. For focusing, the secondary mirror cell can be moved along the optical axis via a linear actuator. The primary mirror is protected by four cover flaps that can be opened via software command. The optical tube assembly is held by a German equatorial mount with a precision encoder system. We will describe the characteristics of the telescope system and summarize our results from on-sky testing such as the achieved optical quality, focus stability and pointing and tracking accuracy.

The main instrument is a fast EMCCD camera with a back-illuminated, frame-transfer sensor, combined with a 10-position filter wheel containing a Sloan filter set. A piggy-back mounted 130mm f/6 refractor and a wide field imager with a commercial 135 mm photo lens complement the setup.

The telescope serves as a training platform for aerospace engineering students in basic astronomy and in remote control of complex systems, and is used from Germany for lectures and courses. M.Sc. and Ph.D. students use it as a research instrument for their engineering and astronomy projects. For SOFIA, it acts as a test platform to evaluate new software and hardware before their integration on the observatory. In some cases, the telescope will also be used to support SOFIA missions by providing preparatory or parallel measurements of a target (astrometry, photometry) or to conduct follow-up observations. The characteristics of the camera also make it an ideal instrument to observe stellar occultations. We will present a selection of use cases and provide an outlook on future plans.

9906-58, Session 15

The Evryscope: design and performance of the first full-sky gigapixel-scale telescope

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The Evryscope is a new type of telescope which covers the entire accessible sky in each exposure. Its 8000-square-degree field-of-view 691 MPix telescope is sensitive to exoplanet transits and other short timescale events not discernible from existing large-sky-area astronomical surveys. The telescope, which places 27 separate individual telescopes into a common mount which tracks the entire accessible sky with only one moving part, is building 1%-precision, many-year-length, high- cadence light curves for every accessible object brighter than ~16th magnitude. The camera readout times are short enough to provide near-continuous observing, with a 97% survey time efficiency. The Evryscope has the largest survey grasp of any current ground-based survey, and is the only existing survey within an order of magnitude of LSST's étendue. We deployed the Evryscope, funded by NSF/ATI, at CTIO in late May 2015. We will present the telescope design, performance, and the first results from the system.

The Evryscope is producing a night-by-night two-minute cadence record of all Southern sky events down to at least 16th magnitude, enabling searches for rapid-timescale variability phenomena ranging from exoplanet transits to gamma-ray-bursts. The system's enormous field of view allows us to simultaneously monitor very large numbers of targets that would otherwise require individual targeting by dedicated telescopes. The Evryscope is sensitive to transiting exoplanets around white dwarfs,

M-dwarfs, and the nearest and brightest stars, and is the first to be able to rapidly monitor most of the sky for nearby-star microlensing events. The Evryscope obtains precise and high-cadence eclipse timing for all Southern eclipsing binaries brighter than 16th magnitude, simultaneously monitors a host of compact-object pulsation and accretion phenomena, and is searching for young stars by their photometric activity. When relatively rare transients events occur, such as gamma-ray bursts (GRBs), nearby supernovae, or even gravitational wave detections from the Advanced LIGO/Virgo network, the telescope will return minute-by-minute light curves and upper limits without needing pointing towards the event as it occurs. By co-adding images, the system will reach V?18 in one-hour integrations, enabling the monitoring of faint objects. Finally, by recording all data, the Evryscope will be able to provide pre-event imaging at two-minute cadence for bright transients and variable objects, enabling the first high-cadence searches for optical variability before, during and after rapid events detected at other wavelengths.

The system has already produced hundreds of thousands of images and over 20TB of data, is meeting our image quality goals, and is achieving at least 5 mmag photometric precision in light curves. We will also present our plans for further development: a Polar Evryscope which takes advantage of the continuous winter darkness in the Arctic and Antarctic to achieve much higher detection efficiency for long-period exoplanets; a world-wide network of telescopes which could cover most of the entire sky continuously 24 hours-a-day; and larger-aperture systems which would be capable of rapidly detecting faint extragalactic events.

9906-59, Session 16

Progress of Antarctic survey telescopes

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The Antarctic Survey Telescope-AST3 consists of three optical telescopes with 680mm primary mirror and 8 square degree field of view, mainly for observations of supernovas and extrasolar planets searching from Antarctic Dome A, where is very likely to be the best astronomical site on earth for astronomical observations according to site testing works jointly by CCAA and UNSW. The second AST3 was mounted on Dome A in Jan. 2015, but the observation had to be stopped due to the frost on the entrance window since May. Anti-frost methods including new electronic control for window ITO heating and active air blowing were designed for the coming maintenance. The anticipated automatic observations will be started from March 2016. The third AST3 is optimized mainly for K band with focal plane outside the main optical tube aiming a better tube seeing and diffraction limited imaging in K band. Now the telescope is under development in NIAOT and the K-band camera is under development in AAO.

9906-60, Session 16

Prototyping and environmental experiments of an aluminum panel for the Dome A 5m terahertz explorer (DATE5)

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Dome A 5m Terahertz Explorer (DATE5) is a proposed telescope to be deployed at Dome A, Antarctica to explore the excellent terahertz observation condition unique to the site. One of the key challenges of the telescope is to realize and maintain the required 10 micron rms overall reflector surface accuracy under the extreme site conditions and unmanned operating mode. Aluminum panels on carbon fiber backup structures is one of the candidate options for the 5 meter main reflector. For aluminum panels, three major technical risks were identified: 1) the large CTE of aluminum causes significant panel deformation due to the large seasonal soak temperature change; 2) internal stress may cause additional surface deformation when operating under a cold environment; 3) reflector panels working at Dome A run high risks of icing (which degrades antenna efficiency and increases noise) and automatic active de-icing mechanisms has to be implemented on the panels. In order to verify the feasibility of the aluminum panels for DATE5 and identify possible technical risks, a prototype panel was fabricated and went through rigorous tests. The manufacture error at the room temperature is 3.2 micron rms, which meets the budget. The panel surface is then measured at various ambient temperatures down to -60oC in a climate chamber using photogrammetric techniques. The additional surface error at the low temperatures is found to be mainly contributed by defocusing error, and the dependence of the panel focal length on temperature is well predictable. No additional surface error caused by internal stress has been observed. Next, the icing condition of the panel is analyzed and a prototype de-icing system based on polyimide film heaters was installed on the panel. The performance of the de-icing system was tested in a climate chamber as well as in the field experiments to simulate a variety of operating environments. The experiments indicate that the power required for de-icing the entire main reflector is less than 1kW and the temperature field produced by the de-icing system has trivial effect on the surface accuracy of the panel. This study indicates that aluminum panels have the potential to meet the reflector surface error budget under the harsh environment of Dome A.

9906-250, Session 16

Nonlinear transient survival level seismic finite element analysis of Magellan 6.5 meter telescopes

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The Magellan Telescopes are a set of twin 6.5 meter ground based optical/near-IR telescopes operated by the Carnegie Institution for Science at the Las Campanas Observatory (LCO) in Chile. The primary mirrors are f/1.25 paraboloids made of borosilicate glass and a honeycomb structure. The secondary mirror provides both f/11 and f/5 focal lengths with two Nasmyth, three auxiliary, and a Cassegrain port on the optical support structure (OSS).

The telescopes have been in operation since 2000 and have experienced several small earthquakes with no damage. Measurement of in situ response of the telescopes to seismic events showed significant dynamic amplification, however, the response of the telescopes to a survival level earthquake, including component level forces, displacements, accelerations, and stresses were unknown. The telescopes are supported with hydrostatic bearings that can lift up under high seismic loading, thus causing a nonlinear response. For this reason, the typical response spectrum analysis performed to analyze a survival level seismic earthquake is not sufficient in determining the true response of the structure. Therefore, a nonlinear transient finite element analysis (FEA) of the telescope structure was performed to assess high risk areas and develop acceleration responses for future instrument design. Several configurations were considered combining different installed components and altitude pointing directions. A description of the models, methodology, and results are presented.

9906-173, Session PS7

Pre-construction results of giant steerable science mirror for TMT

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The results of the prototype will provide more technical support to the preliminary design of GSSM and give more confidence to CIOMP and TMT.

9906-174, Session PS7

Site assembly and testing of the second QUIJOTE telescope

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The QUIJOTE (Q-U-I JOint TEnerife) experiment is a scientific collaboration, led by the Instituto de Astrofísica de Canarias (IAC), with the aim of measuring the polarization of the Cosmic Microwave Background (CMB) in the frequency range 10-40 GHz and at large angular scales (around 1º). The project is composed of 2 telescopes and 3 instruments, located in Teide Observatory (Tenerife, Spain). Idom´s contribution for this project is divided in two phases.

Phase I consisted on the design, assembly and factory testing of the first telescope (2008), the integration and functional tests for the 5 polarimeters of the first instrument (2009), and the design and construction supervision of the building which protects both telescopes (2009), including the installation and commissioning of the mechanism for domes apertures.

Phase II comprised the design, factory assembly & testing, transport and final commissioning on site of the second telescope, which finished in January 2015. The optical design of both telescopes should allow them to reach up to 200 GHz. The required opto-mechanical performance was checked under nominal conditions, reaching a pointing and tracking accuracy lower than 5 arcsec in both axes, 8 times better than specified. Particular inspections and tests were carried out for critical systems, as the rotary joint that transmits fluid, power and signal to the rotary elements, or for the safety system to ensure personnel and hardware protection under emergency conditions.

This paper contains a comprehensive description of the power electronics and acquisition/control design required for safely operation under nominal and emergency conditions, as well as a detailed description of the factory and observatory tests required for the final acceptance of the telescope

9906-175, Session PS8

Astronomical site survey in large Shangri-La area in western China

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During the last 5 years, based on the close collaboration among Chinese astronomical society and the scientists from IfA, NSO, HAO and other institutes, we have successfully developed standard instruments for site survey and applied them to candidate sites distributed in the large Shangri-La area located at the eastern edge of Tibetan plateau. Clear evidence, including the key parameters of seeing factor, sky brightness and water vapor content, has indicated that a few potential sites in the large Shangri-La areas in western China should obtain the excellent astronomical conditions for our purpose to develop large telescopes including solar coronagraph. We introduce the fresh site survey results in this report.

9906-176, Session PS8

The astronomical site selection in the Beni Mellal-Khenifra region

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We use satellite data to conduct a preliminary study on three selected sites in the Beni Mellal-Khenifra region (Morocco). Data refer climatology, cloudy cover, aerosol index and aerosol optical depth. The sites are Tassemit (32?18'33" N, 6?15'28" W, 2248 m), Ghnine (32?12'45" N, 6?21'28"W, 2358 m) and Tazerkounet (32?09'56"N, 6?29'14"W, 1702 m). These sites are easily accessible and not far from the university center of Beni Mellal (Sultan Moulay Sliman University)

9906-177, Session PS8

The University of Tokyo Atacama Observatory 6.5m Telescope: design of mirror coating system and its performances

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We present the mirror coating facility dedicated to a 6.5m infrared-optimized telescope that will be constructed in the University of Tokyo Atacama Observatory (TAO) on the summit of Co. Chajnantor in Atacama. The mirrors have honeycombed structure made from borosilicate for lightweighting and for temperature control. Since it is very delicate, the mirrors must be treated tenderly. Accordingly the coating system will be installed in the support building close to the telescope enclosure.

The reflectivity is over 95% in the infrared wavelength with < 1% in-uniformity. The uniformity of thickness of reflecting film is 10nm (RMS) over the whole mirror. In order to achieve these requests, a conventional evaporation system with a metal pre-wetted filament array is adopted.

The coating chamber is divided into three sections. The upper high vacuum portion of the coating chamber is mounted permanently to the ceiling of the support building. The lower part of chamber is on the movable lifting cart. The primary mirror cell (PMC) is sandwiched between upper and lower chambers for mirror coating process, that is, it makes up a center section of vacuum chamber. To protect the mirror support system and the actuators and to isolate the clean upper portion of the chamber from the dirty lower portion for mirror coating, an inflatable O-ring is adopted.

Since the mirrors must be handled very delicately, the mirror is in the state of looking up and the mirror coating process is performed. That is, evaporators (filaments) are set on above mirror. Therefore the filament with the special shape to prevent drips of the fusion aluminum is requested. Tungsten is used as filament core material. The filament like a spring coil is formed by twisting three tungsten wires. And it is

covered with tungsten net for containing more amount of aluminum and for preventing melted aluminum drip onto the mirrors. The laboratory experiment showed that the thickness of film is 120nm as same as design. Ideal spray pattern will be realized by adjusted filament array configuration and mask pattern.

Old coating film on the mirror has to be removed and the mirror surface should be cleaned up before evaporation. The fixed multi-ring mechanism is adopted for washing system. There are other ideas in this system, for example, many angle controllable spout and center liquid buffer tank. As a result, uniform and stable injection of solvent is achieved. Additionally by air blow system add to cleaning system, uneven residual liquid on the mirror surface is removed. Sodium hydroxide is used to dissolve old aluminum layer as a solvent.

The process of PMC removing from telescope, mirror cleaning, and mirror coating are carried out on same floor level. The PMC is transported by special cart that moves from under telescope to cleaning and coating areas across the bridge connecting telescope enclosure and support building. Since it is necessary to lift up and to lower on each area, the cart has elevator function. The specifications are up to 60ton in lifting load and 1750mm in stroke. It has individual controlled 4 jacking-up motors. Furthermore it has safety braking function on telescope, cleaning, and evaporation positions.

9906-178, Session PS8

Optical turbulence profiles with meteorological data at Aklim site

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The stellar image quality is one of the important criteria used for the selection of the best astronomical sites. However, the turbulence in Earth's atmosphere can seriously limit the resolution of ground based astronomical observation. The study of atmospheric physics shows the importance of some parameters of atmospheric turbulence, such as the structure constant of refractive index fluctuation CN2 , wich characterize the strength of turbulence in the different layers. In the context of this paper we present, first, an example of a CN2 estimated from the National Center for Environmental Prediction/National Center for Atmospheric Research NCEP/NCAR Reanalysis and also from the weather station located at 2m above ground level in Aklim site. Secondly, we will compare it with the profile measured by the Multi-Aperture Scintillation Sensor (MASS), above Aklim Moroccan site (lat.= 30°07'38" N, long.= 8°18'31"W).

9906-179, Session PS8

The 1.56m astronomical telescope retrofitting in the western suburb of Shanghai

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The 1.56m astronomical telescope built in 1980s was designed for astrometric observation. With the expansion of the urban areas, the light pollution has been getting increasingly serious, so that the telescope is no longer suitable for its original scientific objectives. To avoid its getting useless and take advantage of its mirror power, we decide to retrofit the telescope to make it capable of doing a very different job, satellite laser ranging, collaborating with the adjacent International Laser Ranging Station of Shanghai.

To achieve the goal, the telescope must be able to track artificial satellites with the accuracy as high as a few arcseconds and the speed as high as 1 to 2 degrees per second, hundreds of times higher than its original tracking speed of diurnal motion. In addition, tracking a star just need moving the right ascension axis, while tracking a satellite must move both axes.

We installed two incremental grating encoders on both axes with 2 readheads each to compensate for the effect of bearing wander and eliminate odd error harmonics, including eccentricity. We removed a worm gear to reduce the transmission ration from 12500 to 625 and installed two 5kw servo motors. We installed new instrumentation for laser ranging, in the first phase just as a co-receiver of the adjacent 60cm laser ranging telescope, and developed new software.

After entering commissioning phase, a serious problem arose. The RA axis jittered severely while tracking at high speed. After analysis, we believed the problem was caused by the hydrostatic bearings of the RA axis. We tried to lower the oil pressure to reduce the oil film thickness, in order to increase friction i.e. damping, and the problem improved. This method however did not completely solve the problem, because the oil pressure was unstable and the film thickness is also affected by the viscosity changing with temperature.

Therefore, we tried many other methods. An oil pressure controller was installed to stabilize the oil pressure. We used a new oil with low water absorption and a viscosity that does not vary unacceptably over the common temperature. We re-adjusted the balance of the telescope mount under the condition of worm gear detached, because unbalanced torque may cause the oil pad bearing unstable.

Unfortunately, after all the attempts, the problem was not improved significantly. Now we are considering to restore the RA axis transmission rate back to 12500 from 625, in order to prevent it from jittering at the expense of speed and noise and so forth.

9906-180, Session PS8

A new test environment for the SOFIA secondary mirror assembly to reduce the required time for inflight testing

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The Stratospheric Observatory For Infrared Astronomy (SOFIA) reached its full operational capability in 2014 and takes off from the NASA Armstrong Flight Research Center to explore the universe about four times a week. Maximizing the program's scientific output naturally leaves very little flight time for engineering tasks such as implementation and testing of improved software and hardware. Consequently it is very important to have a comparable test environment and infrastructure to perform troubleshooting, verifications and improvements on ground without interfering with science missions. SOFIA's Secondary Mirror Mechanism (SMM) is one of the most complex systems of the observatory. Since it is the only actively controlled element in the optical path its improvement offers great potential for influencing the whole observatory's performance. A primary goal has been to identify and characterize a 300Hz structural resonance frequency that limits the SMM's performance. In 2013 a first simple laboratory mockup of the mechanism was built to perform basic controller tests in the lower frequency band of up to 50Hz. This was a first step to relocate required engineering tests from the active observatory into the laboratory. However, to test and include accurate filters and damping methods as well as to evaluate hardware modifications, a more precise mockup is required that represents the system characteristic over a much larger frequency range. Therefore the mockup has been improved in several steps to a full test environment, representing the system dynamics with high accuracy. This new ground equipment allows moving almost the entire secondary mirror test activities away from the observatory.

As fast actuator in the optical path, the SMM also plays a major role in SOFIA's pointing stabilization concept. To increase the steering bandwidth, hardware changes are required that ultimately need to be evaluated using the telescope optics. To minimize the impact on science time, the laboratory test setup will be expanded in the near future with an optical measurement system so that it can be used for the vast majority of the testing.

This contribution describes the current laboratory test environment for the SOFIA Secondary Mirror Mechanism including its previous design steps. Moreover, an outlook is presented about the expansion with an optical measurement setup including a fast camera feedback and a fast steering mirror to induce simulated in-flight image disturbances. By using a camera very similar to SOFIA's focal plane guider camera, this optical test setup will also allow for investigation of the potential for image motion compensation for SOFIA with a SMM of increased bandwidth.

9906-181, Session PS8

Statistics of meteorological and 225 GHz opacity data for early science 2014-ES3 period of the Large Millimeter Telescope

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The Large Millimeter Telescope (LMT) located in Sierra Negra Puebla, Mexico has started its early science programs since 2013, to achieve its exceptional performance a large effort has been put into the alignment and control of the antenna, calibration, readout and pipeline of the scientific receivers, as well as on the meteorological monitoring instrumentation. In this paper we present statistical data taken with our weather station and 225 GHz radiometer for the first full season of eight months (2014-ES3) of the LMT. The weather and opacity data provide important information to astronomers to allocate scientific observations and calibrate data, and plays an important role to technical staff to schedule maintaining operations at the telescope.

9906-182, Session PS8

Telescope site survey at the US Naval Observatory, Flagstaff station

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The US Naval Observatory (USNO) anticipates the installation of a new telescope (2m-4m class) at the Naval Observatory Flagstaff Station (NOFS). In support of this project NOFS personnel will conduct a site survey on NOFS property and at a few nearby locations on government land. The survey will include seeing measurements using differential image motion monitors (DIMM) and sky brightness measurements using all-sky cameras. In addition, analysis of integrated precipitable water (IPW) measurements made by a near-by National Oceanic and Atmospheric Administration (NOAA) station will be discussed with respect to site thermal infrared capability. NOFS history and status, measurement methodologies, and preliminary results will be presented.

9906-184, Session PS8

Collecting various sustainability metrics of observatory operations on Mauna Kea

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Situated on Maunakea, the Canada France Hawaii Telescope has a variety of operations components at the summit and in a headquarters facility in Kamuela, HI. The observatory operates a fleet to shuttle between facilities and also maintains two computer server rooms at their two locations. Both building facilities have specific consumption levels in energy, water use and waste generated. Other facets such as employee air travel for meeting and conferences such as SPIE also have measurable profiles. By collecting metrics in these categories, the collective impact of CFHT and other observatories operations on the Maunakea Astronomy Precinct can be estimated. An audit of carbon emissions in these aspects as well as specific efficiency metrics such as data center Power Use Efficiency gives a general scale of environmental and social alterations. Measurables can be gathered in use phases as well as throughout the lifecycle, especially in energy intensive categories. Applications of the audit would be for such things as crafting sustainability strategies.

While many observatories are located at remote or uninhabited sites, the observatories in the Maunakea Astronomy Precinct benefit from a solid infrastructure on the Big Island of Hawaii. To keep astronomy sustainable in this environment requires presenting a clear picture of impact to the various stakeholders made up of government, businesses, local population and collaboration groups. Current assessments can establish a baseline for future proposals as well as highlight present best efforts to interested stakeholders. Within CFHT, some best efforts with a projected positive impact are the use of renewable energy system, remote automation and designing for the environment.

Beyond applications for a sustainability strategy, a few items such as new telescope construction, engineering for an observatory site reuse, a master lease renewal and an environmental impact statement can benefit from metrics on impact. The master lease for the reserve in which the Astronomy Precinct is situated expires in 2033 and thus work for supporting documents is taking shape now. New and reuse facilities are anticipated to take shape in the meantime.

Having switched to remote observing in January of 2011, CFHT already has a system in place that gathers facility metrics at the summit and has now archived a few year's worth of operations data. This along with other systems that have tracked fleet use, and data center statistics can be assessed for resource intensity by using carbon emissions as a common measurement.

Work for the study was done in collaboration with the University of Wisconsin at Madison through the Sustainable Systems Engineering Program.

9906-186, Session PS8

Atmospheric phase characteristics of the ALMA long baseline

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Atacama Large Millimeter/submillimeter Array (ALMA) is the world's largest mm/submm interferometer. Along with science observations, ALMA has performed several long baseline campaigns in the last 5 years to characterize and optimize its long baseline capabilities. To achieve full long baseline capability of ALMA, it is important to understand the characteristics of atmospheric phase fluctuation at long baselines, since it is believe to be the main cause of mm/submm image degradation. We present here, for the first time, detailed properties of atmospheric phase fluctuation at mm/submm wavelength from baselines up to 15 km in length. Atmospheric phase fluctuation increases as a function of baseline length with a power-law slope close to 0.6, and many of the data display a shallower slope (0.2 - 0.3) at baseline length greater than about 1 km. Some of the data, on the other hand, show a single slope up to the maximum baseline length of around 15 km. The phase correction method based on water vapor radiometers (WVRs) works well, especially for cases with precipitable water vapor (PWV) greater than 1 mm (i.e., when the amount of water vapor in the atmosphere is significant), typically yielding a 50% decrease or more in the degree of phase fluctuation. However, significant amount of atmospheric phase fluctuation still remains after WVR phase correction; about 200 micron in root-mean-square (rms) excess path length (rms phase fluctuation in unit of path length) even at PWV less than 1 mm. This result suggests the existence of other non-water-vapor sources of phase fluctuation, and emphasizes the need for additional phase correction methods, such as the fast switching. The fast switching phase correction method has been simulated using observations of single sources, and result suggests that it works best with short cycle time; the phase coherence linearly improves with the cycle time.

9906-187, Session PS8

Development of the optical laser system for testing and checking equipment for transmitting and receiving terminals of the space optical communication line

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Development of the high-speed and reliable space laser communication systems is of current interest for the space instrumentation. Thus, it is necessary to test working characteristics of the terminals in laboratory conditions. The task in that case is to create the high precision optical system, with minimum self errors, and to provide absence of external influence to the laser beam structure during measurements. One of these effects is the influence of the refraction index inhomogeneity inside the medium of propagation to the measurement parameters.

The goal of the work is to develop the control and verification equipment (CVE) intended for the laboratory testing of the space optical communication line (SOCL) and to define the statistical characteristics of the laser beam during its propagation through the air space of the imitative optical track. This is necessary to determine the ability of performing of precision angular measurements in presence of the atmosphere. CVE should test:

1. The form and the width on the half maximum of the directivity diagram of the SOCL beams.

2. Coincidence of the axes of the detector and the transmitter of the SOCL.

3. The coinciding process of SOCL axis with the CVE beam axis during the entering to the communication and during the tracking (with the given angular movement velocity CVE)

4. The working-off process for the beam capture and tracking system of the SOCL during the imitations of the SOCL mounting platform vibrations, and also the background illuminations by the illuminated surface of the Earth and the solar disk.

CVE consists of two channels. The first, transmitting channel forms the beam that imitates the radiation of the distant correspondent which is directed to the tested module SOCL. The receiving channel forms a far-field distribution of the received radiation and compares it with the reference distribution. With various conditions of the tested module (imitations of the vibrations of the mounting platform, correspondent movements, background illumination, modulation amplitude variations of the radiation) the work of the capture and tracking system can be controlled by the coincidence of the axes of the directivity diagram for the tested module and reference beam.

To check out of the CVE system the model was created. The main algorithms of the adjustment and self-test were tested. The statistical characteristics of the laser beam with the wavelength of 1,06 microns and the diameter of 50, 100, 200 mm passed through the 40-m air layer in enclosed laboratory conditions (the dispersion of the half-width of the far-field distribution and roaming of its center of gravity) were measured.

With the results obtained the conclusions of the ability of the complex tests of the SOCL apparatus in the laboratory conditions were made.

9906-188, Session PS8

The Calern atmospheric turbulence station

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The Observatoire de la Côte d'Azur and the J.L. Lagrange Laboratory have a long and confirmed expertise in Atmospheric Optics. This expertise allowed this team to participate in the selection of the major sites of all the greatest projects of existing telescopes in particular of the 8-10 meter class: GranTeCan in the Canary Islands, the European VLT and Southern Gemini in Chile, Keck, Northern Gemini & Subaru in Hawaii. With a unique set of instruments to probe the atmospheric turbulence, the Lagrange Laboratory was involved in the site selection of the future Extremely Large Telescopes (ELT) as the 40m European E-ELT and the 30m American TMT. Our team was also in charge of the qualification of the site of Dome C in Antarctica whose potential is Astronomy is considerable.

In the continuity of this long tradition, the Calern Observatory now benefits of a station of atmospheric turbulence measurement (CATS: Calern Atmospheric Turbulence Station). This station is a response to real needs in support of other projects that will give additional dynamic to the Calern Observatory. This is mainly to improve the link budget of Laser Telemetry from MeO station and generally free space optical links. It is also supporting projects to equip MeO and C2PU telescopes with Adaptive Optics systems in the context of a real synergy between researchers and engineers from different laboratories and institutes.

The CATS station is equipped with a set of complementary instruments for monitoring atmospheric turbulence parameters. These new-generation instruments are autonomous within original techniques for measuring optical turbulence since the first meters above the ground to the borders of the atmosphere. One of the CATS instruments is the PML (Profiler of Moon Limb) measuring the vertical distribution of turbulence using lunar and solar edges. The second instrument, called G-DIMM for Generalized DIMM, is dedicated to provide wavefront parameters at ground level (seeing, outer scale, time coherence and isoplanatic angle). In order to avoid the surface layer, the G-DIMM instrument is installed on a platform at 4m above the ground (PML insensitive to this layer can remain on the ground). To protect our instruments from bad weather conditions (rain,

snow, wind) that occur on the Calern site, GDIMM and PML are sheltered under domes that close automatically. These instruments are installed near the MeO telescope.

The CATS station is also a support for our training activities as part of our Masters IMAG2E and OPTICS, through the organization of on-sky practical works. We are also considering the organization of international summer schools and workshops on the techniques of Atmospheric Optics and Site-Testing in Astronomy around the CATS station.

9906-189, Session PS8

Oukaimeden Observatory: ground meteorology

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In this paper we present the results of the ground meteorological properties obtained analyzing a long time series of data taken at one of the most important astronomical observatories in the world: Oukaimeden Observatory in High-Atlas of Morocco.

These data were obtained from January 2011 to December 2014 making use of automatic weather stations (AWSs) equipped with standard meteorological sensors providing the air temperature, relative humidity, barometric pressure, wind speed, and wind direction

9906-190, Session PS9

Support optimization of the ring primary mirror of a 2m solar telescope

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A special 2-m Ring Solar Telescope (2-m RST) is to be built by YNAO. Its distinct primary mirror is shaped in a ring with an outer diameter of 2.02 m and a ring width of 0.35 m. Careful calculation and optimization of the mirror support pattern have been carried out first of all to define optimum blank parameters in view of performance balance of support design, fabrication and cost. This paper is to review the special consideration and optimization of the support design for the unique ring mirror. Schott zerodur is the prevailing candidate for the primary mirror blank. Diverse support patterns with various blank thicknesses have been discussed by extensive calculation of axial support pattern of the mirror. We reached an optimum design of 36 axial supports for a blank thickness of 0.15 m with surface error of ~5 nm RMS. Afterwards, lateral support scheme was figured out for the mirror with settled parameters. A classical push-and-pull scheme was used. Seeing the relative flexibility of the ring mirror, special consideration was taken to unusually set the acting direction of the support forces not in the mirror gravity plane, but along the gravity of the local virtual slices of the mirror blank. Nine couples of the lateral push-pull force are considered. When pointing to horizon, the mirror surface exhibits RMS error of ~5 nm with three additional small force couples used to compensate for the predominant astigmatism introduced by lateral supports. Finally, error estimation has been performed to evaluate the surface degradation with introduced errors in support force and support position, respectively, for both axial and lateral supports. Monte Carlo approach was applied using unit seeds for amplitude and position of support force. The comprehensive optimization and calculation suggests the support systems design meet the technic requirements of the ring mirror of the 2-m RST.

9906-191, Session PS9

DKIST facility management system integration

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The Daniel K. Inouye Solar Telescope (DKIST) Observatory is under construction at Haleakala, Maui, Hawaii. When complete, the DKIST will be the largest solar telescope in the world. The Facility Management System (FMS) controls the Facility Thermal System (FTS) including the Carousel Cooling System, the Telescope Chamber Environmental Control System, and the Temperature Monitoring System. It will also integrate the Power Energy Management System, and several service systems such as HVAC, the Domestic Water Distribution System, and the Vacuum System. All of these subsystems must operate in coordination to provide the best possible observing conditions and overall building management. In doing so, the FMS must actively react to varying weather conditions and observational requirements. In addition, the impact of the facility must not interfere with neighboring installations while operating in a very environmentally and culturally sensitive area. The FMS system will be comprised of five Programmable Automation Controllers (PACs). I present the current standing, challenges, and plan to integrate all of the FMS subsystems.

9906-192, Session PS9

Daniel K. Inouye Solar Telescope optical alignment plan

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The Daniel K. Inouye Solar Telescope (DKIST) is a 4-meter solar telescope under construction at Haleakala, Hawaii. The challenge of the DKIST optical alignment is the off-axis Gregorian configuration based on an altitude-azimuth mount, the independently-rotating Coudé platform and the large number of relay mirrors. This paper describes the optical alignment plan of the complete telescope, including the primary 4.24-m diameter off-axis secondary mirror, the secondary 620 mm diameter off-axis mirror, the transfer optics and the Coudé optics feeding the wavefront correction system and the science instruments. A number of accurate metrology instruments will be used to align the telescope and to reach the performances, including a laser tracker for initial positioning, a theodolite for accurate tilt alignment, a Coordinate Measurement Machine (CMM) arm for local alignment in the Coudé room, and a Shack-Hartmann wavefront sensor to characterize the aberrations by measuring selected target stars. The wavefront will be characterized at the primary focus, the Gregorian focus, the intermediate focus and at the telescope focal plane. The laser tracker will serve also to measure the mirrors positions as function of altitude angle due to the Telescope Mount Assembly (TMA) structure deflection. This paper describes also the method that will be used to compute the compensating mirrors shift and tilt needed to correct the residual aberrations and position of the focal plane.

9906-194, Session PS9

The COSMO coronagraph optical design and stray light analysis

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The COronal Solar Magnetism Observatory Large Coronagraph (COSMO-LC) is a 1.5 meter Lyot coronagraph dedicated to measuring magnetic fields and plasma conditions in the corona and chromosphere of the Sun. The COSMO-LC is designed to measure weak magnetic fields (1 gauss) in the solar corona by observing the polarization of coronal emissions lines from 530-1100nm using a filtergraph instrument. COSMO-LC will have a 1 degree field of view to observe the full solar corona out to 1 solar radii beyond the limb of the sun with a spatial resolution of 2 arc-seconds per pixel (4k X 4k detector). The large Etendue of the system presents challenges to the design of the optical system and the narrow band birefringent filter. The LC employs a 1.5 meter refractive objective lens and an all refractive optical system. The birefringent filter was designed using high index Lithium Niobate crystals. The most critical part of the coronagraph is the objective lens that is exposed to direct sunlight several million times brighter than the corona. The objective lens (O1) must scatter as little light as possible, on order a few parts per million. This is accomplished through choice of the glass and specification of the surface polish. In this paper we discuss the optical design of the COSMO-LC and the detailed design of the O1 and other elements that keep stray light to a minimum. The result is an instrument with stray light below 5 millionths the brightness of the sun 50 arcseconds from the sun. The COSMO-LC has just had a Preliminary Design Review and the post PDR design will be presented.

9906-195, Session PS9

Pointing a solar telescope

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As far as pointing is concerned, a solar telescope is merely an ordinary astronomical telescope but with enhancements for observing solar and coronal features. The paper discusses the additional coordinate systems that need to be supported, shows how to generate the required solar ephemerides (both orbital and physical), and sets out a suitable application programming interface for the telescope control system to use when making solar observations.

9906-197, Session PS10

The upgraded telescope control system performance for the Canada-France-Hawaii Telescope

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The Canada-France-Hawaii Telescope (CFHT) completed the first phase of its TCS upgrade in early 2015. Prior to this effort, the previous version of CFHT's TCS was largely unmodified since it began operation in 1979 and had begun to exhibit reliability and maintainability issues entering its third decade of operation. The first phase consisted of replacing the custom built servo control hardware built by the Canadian Marconi Company with an off-the-shelf Delta Tau Systems Power PMAC and replacing the absolute and incremental encoders with modern equivalents. Adapting the motion control algorithms used within the Power PMAC for real-time control of the telescope on the sky posed unique challenges. This work will briefly summarize the design for the upgraded TCS at CFHT, describe the solutions that adapted the traditional use of the Power PMAC for use at CFHT, and discuss the improved performance of CFHT's new TCS in terms of decreased time to target and decreased tracking error.

9906-198, Session PS10

Time synchronization diagnosis and enhancements at GTC telescope

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GTC, among the largest ground based optical infrared telescopes, has been now fully operative for 7 years. Besides major upgrades, maintenance activity still finds glitches that are difficult to isolate as these don't affect daily operations but appear erratically only under some circumstances. Sometimes, hidden problems are more relevant than expected, as is the case of a recently discovered issue with Time Service, that just shows up eventually during Leap Second adjustment. It is surprising that errors are still found in the system that have been under inspection since day one. This becomes even more strange when this errors lay inside one of the backbone services of a large telescope: Time Synchronization.

On every telescope it is crucial to maintain a perfect time reference as a Swiss watch. One does not only need a high precision pointing, to aim stars accurately but as time goes by the earth and some celestial objects with proper motion change its relative position, so tracking is required that means targeting at different directions on every precise moment. Furthermore, mechanical and optical effects are considered with a pointing model and optomechanics close loops, as well as atmospheric turbulence are compensated with guiding and even adaptative optics. But this target-earth-telescope synchronization, is not the single requirement for having a perfect time source, there are other reasons that makes Time Service extremely important in modern distributed environments: the synchronization of different subsystems of telescope control platform in real-time.

Talking about Time, often known as 4th dimension, is conceptually easy, as long as it moves forward in a linear way as in our daily experience. But when it behaves otherwise, jumping into the future or into the past, it can be mindbreaking, becoming even more difficult while analyzing past situations when time leaps took place, and it became more challenging when software running is not aware about the possibility of these time travels.

Beyond philosophical implications this paper emphasizes the importance to analyse Time Service in large Telescope control platforms as a way to avoid many mysterious and eventual issues that normally are difficult to diagnose with standard FMECA analysis in an environment where many CPU collaborate to perform tasks while their respective clocks are forward or backward changed every few seconds while they believe their time reference is immutable.

Furthermore, as an example, GTC Time Service issue is presented jointly with corrective actions taken and several recommendations for future developments in terms of real-time distributed process design, test and acceptance, now considering time frame health as baseline analysis of every single side of a Telescope control system.

9906-199, Session PS10

An observatory control system for the University of Hawai'i 2.2m Telescope

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The University of Hawai'i 2.2m telescope at Maunakea has operated since 1970, and has had several controls upgrades to date. Previous incarnations include a console-driven LSI computer with custom servo control electronics, installed in the late 1970s, and a more recent system built around a GNU/Linux server with Galil PCI motion controller card which was developed starting in 1999. This outgoing system has proven itself over the past 15 years, but also represents a compromise between a fully modern, easily maintainable and upgradable system, and a low-cost replacement for mainly the central software and servo controls while using original wiring and relay logic. As parts and subsystems have been replaced due to failure, new instruments have required control software modification, and typical operations move towards fully robotic and unattended, a complete replacement and upgrade was deemed appropriate. The new system will operate as a distributed hierarchy of GNU/Linux central server, networked single-board computers, microcontrollers, and a modular motion control processor for the main axes. The software is written to modern standards, and will be shared under "open source" license terms. Design hardware is widely available and inexpensive where possible, including Raspberry Pi and Arduino systems. Rather than just a telescope control system, this new effort is towards a cohesive, modular, and robust whole observatory control system, with design goals of fully robotic unattended operation, high reliability, and ease of maintenance and upgrade. We discuss the design methodology, software and hardware implementation details, and process of installing and testing this highly modular and robust observatory control system.

9906-200, Session PS10

A new mix of power for the ESO installations in Chile: greener, more reliable, cheaper

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The highest quality demands for astronomical research impose to locate observatories often in areas not easily reached by the existing power infrastructures. At the same time, availability and cost of power is a primary factor for sustainable operations. Power may also be a potential source for CO2 pollution. As part of its green initiatives, ESO is in the process of replacing the power sources for its own, La Silla and Paranal, and shared, ALMA, installations in Chile in order to provide them with more reliable, affordable, and smaller CO2 footprint power solutions. The connectivity to the Chilean interconnected power systems (grid) which is to extensively use non-conventional renewable energy (NCRE) as well as the use of less polluting fuels wherever self-generation cannot be avoided are key building blocks for the solutions selected for every site. In addition, considerations such as the environmental impact and - if required - the partnership with other entities have also to be taken into account. After years of preparatory work to which the Chilean Authorities provided great help and support, ESO has now launched an articulated program to upgrade the existing agreements/facilities in i) the La Silla Observatory, from free to regulated grid client status due to an agreement with a Solar Farm private initiative, in ii) the Paranal Observatory, from local generation using liquefied petroleum gas (LPG) to connection to the grid which is to extensively use NCRE, and last but not least, in iii) the ALMA Observatory where ESO participates together with North American and East Asian partners, from replacing the LPG as fuel for the turbine local generation system with the use of less polluting natural gas (NG) supplied by a pipe connection to eliminate the pollution caused by the LPG trucks (currently 1 LPG truck from the VIII region, Bio Bio, to the II region, ALMA and back every day, for a total of 3000km). The technologies used and the status of completion of the different projects, as well as the expected benefits are discussed in this paper.

Go green is a common buzzword nowadays and the expectations are high. 100% green energy may not always be economically affordable. The paper provides insight on the technical and economical drivers for each of the three different solutions ESO has adopted. Each following a different philosophy, but all aimed to reduce the overall CO2 footprint, for which a calculation of the expected benefit is also provided. Last but not least, the paper dedicates some space to the discussion of the handling of the environmental permits needed to allow this type of projects to take place in Chile, an aspect that need due attention when new projects and/or improvement to existing one is planned.

9906-201, Session PS10

New-life for the THEMIS solar telescope

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The THEMIS telescope is a 90 cm solar telescope designed for multiline spectropolarimetry in the 400-1100 nm range. Its main application is for solar surface studies, although Mercury and other planets have been important targets within a 15 years exploitation period. The alt-az helium-filled telescope is connected to a large predispersor/ spectropgraph through a complex optical relay. Themis routinely delivers high SNR polarized spectra with a polarimetric accuracy of 10-4 to 10-5. The polarimetric system uses a modulated dual beam principle with an analyzer located at the prime focus. Due to this configuration, Themis has been called a "polarization -free" telescope (although a better qualification would be "calibration-free"). Speckle imaging has been successfully implemented showing that the telescope has excellent imaging capabilities whenever the seeing is above r0=8cm. The present upgrades aim at correcting a number of limiting issues: i) Polarized spectra require high-SNR hence long exposure times, and the mapping the solar surface is also a time consuming process: as a result, the spectropolarimetry spatial resolution is never better than 0.5" which is no longer a competitive number, ii) The current dual beam polarimetry requires a severe field limitation to 15" in one spatial direction, which is both an observing limitation and makes impossible the implementation of any wavefront sensor, and iii) There is a flaw at system level in the placement of the current scanning device.

To solve what precedes, a 2 years study was necessary. A re-designed optical path starting from the M2 is being implemented, changing the f/ratio from f/63 to f/52.9. The optical relay is simpler with an improved transmission, and an AO bench will be located just before the spectrograph entrance. This AO is designed to start operating at r0=4.7 cm (half of the time at our site) with a ~100 actuator high-speed and high-stroke DM. The new polarimetric concept is now a superimposed modulated dual beam with no field limitation: this is the most challenging part of the work as it implies to control the behaviour of the Mueller matrix of a time-varying complex optical system. Based on a complete model of the optical path, with detailed simulations of the effect of ad-hoc surface coatings, deviation from the ideal situation can be controlled to an almost arbitrary low level . We expect from this renewed telescope a very large improvement of the spatial resolution of the polarized spectra, an excellent performances in spectrolarimetric mapping of the solar surface. It will available during a second exploitation period within 2018 -2025 and will then stop operating at the dawn of the future European Solar Telescope (EST).

9906-202, Session PS10

Commensal low frequency observing on the NRAO VLA: VLITE status and future plans

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The National Radio Astronomy Observatory's Jansky Very Large Array (NRAO VLA) has undergone an upgrade to a broadband system operating in the frequency range of 1-50 GHz. The US Naval Research Laboratory (NRL) has collaborated with NRAO to develop a new broadband low frequency receiver operating at 56-86 MHz (4-band) and 240-470 MHz (P-band). The P-band system is in regular operation as a user facility on the VLA and the 4-band system is currently undergoing new feed development.

The low frequency feeds on the VLA are located at the prime focus while the 1-50 GHz feeds are at the Cassegrain focus. NRL has taken advantage of this uniqueness in feed location to expand the VLA low frequency capabilities in an experimental system. NRL and NRAO have developed, installed, and commissioned a new commensal system called the VLA Lowband Ionospheric and Transient Experiment (VLITE). Dedicated samplers and fibers tap the signal from 10 VLA P-band receivers and correlate those through a custom-designed real-time DiFX correlator. The operation of VLITE requires no additional resources from the VLA system running the primary science program. VLITE commensal operations run in parallel during nearly all Cassegrain programs.

VLITE operates with a 64 MHz bandwidth centered at 352 MHz with 100 kHz spectral resolution and 2 s temporal resolution. The low band feeds provide linear polarization to the correlator and all four correlation products are produced. The key components of the VLITE system are the large field-of-view (5 square degrees) and continual operation. The commensal system greatly expands the science capabilities of the VLA through enhanced data products to the primary science program while at the same time opening a new window on searches for astrophysical transients, enabling stand-alone astrophysics, and allowing real-time ionospheric studies.

In the first year of operation VLITE recorded data at 71% wall time for a total of 6300 hours on the sky and VLITE scans have covered more than 50% of the sky above declinations of -40 degrees to depths greater than 30 seconds. The total on-sky time for the VLITE system over a year is nearly 30 times the on-sky time for the PI-driven low frequency system on the VLA in the year prior to VLITE deployment.

The narrow bandwidth (64 MHz) and small number of antennas (10) allowed the initial experimental system to be built through an expansion of the CPU-based DiFX correlator. Plans to expand the test system to a full Lowband Observatory (LOBO) correlating all 27 VLA antennas across the full low frequency band would require an increase of a factor of 50 in correlation capability.

9906-203, Session PS10

Implementation of W. M. Keck Observatory's Telescope control system upgrade

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The W. M. Keck Observatory's two 10 m telescopes have been operating for the past 25 years with the original technology and infrastructure for its major control systems. Decreasing performance and equipment break-downs have put a heavy burden on the operations and maintenance crew keeping performance at the level needed for efficient and reliable science operations. In 2009, the Telescope Control System Upgrade (TCSU) project was launched to address the need for improved telescope pointing, tracking, and offsetting performance as well as better maintainability and reliability. The TCSU project has replaced all of the major elements of the telescope control system, rotator and secondary mirror controls, and safety system. Obsolete and custom equipment is being replaced with new solutions based on commercial off the shelf equipment. New telescope encoders and the addition of tilt meters are providing better position sensing. An improved pointing model and new telescope mount control architecture are providing better closed loop position and velocity control. Finally, a switching solution using solid state relays and dual network switches was installed to provide seamless and rapid switching between the old and new systems. This has successfully minimized testing impact on operations during commissioning. The implementation of the TCSU project has been successful and provides performance improvements and maintainability that will meet the demanding needs of the observatory over the coming decades.

9906-204, Session PS10

LSST communications middleware implementation

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The LSST communications middleware is based on a set of software abstractions; which provide standard interfaces for common communications services.

The observatory requires communication between diverse subsystems, implemented by different contractors, and comprehensive archiving of subsystem status data.

The Service Abstraction Layer (SAL) is implemented using open source packages that implement open standards of DDS (Data Distribution Service) for data communication and SQL (Standard Query Language) for database access.

The OpenSplice (Prismtech) Community Edition of DDS provides an LGPL licensed distribution which may be freely re-distributed. The availability of the full source code provides assurances that the project will be able to maintain it over the full 10 year survey, independent of the fortunes of the original providers.

For each subsystem, abstractions for each of the Telemetry datastreams, along with Command/Response and Events, have been agreed with the appropriate component vendor (eg Dome, TMA, Hexapod) and captured in ICD's (Interface Control Documents).

The definition of instances of these abstractions is tightly controlled by reference to a system dictionary. All code referencing them is automatically generated and includes real-time consistency checking on a per-transaction basis. All Command transactions, Telemetry, and Event messages, are automatically stored in a system wide "Facility Database" system.

The EFD cluster is comprised of a set of COTS 1U rack mount servers, each supporting 4x 8Gb storage units (currently baselined as SATA HD, but solid state may be substituted depending upon price/performance).

The full set of defined transactions (per subsystem) is formally described using XML Schema. The XML is then used to automatically generate DDS compliant Interface Definition Language (IDL). The IDL is also extended with a set of SAL specific metadata which provides real-time consistency checking, clock slew detection, and full traceability on a per message basis.

The code (supported languages include C++,Java,Python,LabVIEW) to support the complete set of SAL mediated communications is automatically generated, along with a comprehensive set of unit tests, and extensive documentation. Application writers need only the appropriate runtime packages (SAL + DDS Shared libraries or Jar archives) in order to communicate with any other subsystem.

9906-205, Session PS10

Scientific planning for the VLT and VLTI

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An observatory system like the VLT/I requires careful scientific planning for operations and future instruments. Currently the system includes four 8m telescopes, four 1.8m telescopes used exclusively for interferometry, two 4m telescopes and 2 survey telescopes. The VLT offers a large range of scientific capabilities and setting the corresponding priorities depends on community interactions and the definition of future instrumentation. Coordinating the existing and planned instrumentation is an important aspect for strong scientific return. The current scientific priorities for the VLT and VLTI are pushing for the development of the highest angular resolution imaging and astrometry, integral field spectroscopy and multi-object spectroscopy. The ESO 4m telescopes on La Silla will be dedicated to time domain spectroscopy and exo-planet searches with special instruments. The next decade will also see a significant rise in the scientific importance of massive ground and space-based surveys. We discuss how future developments in astronomical research could shape the VLT/I evolution.

9906-206, Session PS10

Planet imaging polarimetry with the solar telescope GREGOR

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Polarimetry of planets and planetary systems provide unique information on physics and chemistry of planetary atmospheres. We have built a new system which includes fast polarimetric modulation, high-rate readout CCD, and adaptive optics. It operates at the solar telescope GREGOR on Tenerife, Canary Islands, and it benefits from the possibility to calibrate the entire optical train after the secondary mirror. Here we presents the system design, performance tests, and first scientific data. This research is supported by the ERC Advanced Grant HotMol.

9906-61, Session 17

SOFIA: the first two years of full operation *(Invited Paper)*

Alfred Krabbe, Deutsches SOFIA Institut (Germany) and Univ. Stuttgart (Germany)

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is about two years into its regular operation.

After ramping up the flight frequency and the observing efficiency, SOFIA is now operating at about 90% of its schedulable science flight capacity. While SOFIA is the only astronomical observatory addressing the far infrared electromagnetic spectrum, its suite of cameras and spectrometers covers nearly 3 orders of magnitude in wavelength space. During the last two years, three instruments have been commissioned: FIFI-LS, upGREAT, and FPI+. More upgrades and instruments are awaiting their deployment at the telescope. The presentation will touch on the status and progress of SOFIA and also demonstrate its unique science capabilities by sharing some of the highlights, which have been obtained.

9906-62, Session 17

SOFIA secondary mirror mechanism heavy maintenance and improvements

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The Stratospheric Observatory For Infrared Astronomy (SOFIA) reached its full operational capability in 2014 and completed hundreds of observation flights. Since its installation in 2002, the secondary mirror mechanism was subject to thousands of operating hours equivalent to millions of load cycles. During the aircraft heavy maintenance in fall 2014, a four month time window enabled the removal of the mechanism from the telescope structure for improvements and service. Next to visual corrosion- and crack-inspection of the flexures, critical electronic components (in particular the set of three eddy current position sensors that determine the mirror tilt) were replaced. Moreover a detailed temperature dependent position calibration of the system was performed in a cold chamber to improve the pointing accuracy. Until then, a simple temperature independent linear gain was used to translate the sensor output voltage into a position. For accurate positioning over the whole temperature range, a temperature dependent correction function had to be developed. This calibration would have cost hours of observing time when performed in flight which made it an essential goal for completion during the maintenance period. An autocollimator was used as optical reference camera to measure the tip-tilt position of the secondary mirror in the cold chamber. Using this calibration setup, a pattern of many mirror positions in the tip-tilt domain was approached at several temperature points to provide a high resolution data set for the new multidimensional calibration function. Later in-flight verification measurements confirmed a large improvement in pointing accuracy when including the temperature measurements into the position correction. Improvements were especially noticed in the lower temperature range of up to a factor of 10. This contribution provides an insight into the work performed during the SOFIA - Secondary Mirror Mechanism maintenance with the focus on the temperature dependent position calibration.

9906-63, Session 17

The design and development of a high-resolution visible-to-near-UV telescope for balloon-borne astronomy: SuperBIT

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Balloon-borne astronomy is unique in that it allows for a level of image stability and resolution that is comparable to space-borne systems due to greatly reduced atmospheric interference, but at a fraction of the cost and over a significantly reduced development time-scale. As such, for instruments operating within the visible-to-near-UV bands, a theoretical diffraction limited resolution of 0.01" is achievable from the stratosphere (35-40 km altitude) without the need for extensive adaptive optical systems required by ground-based systems. The Balloon-borne Imaging Telescope (aka. SuperBIT) is an wide-field instrument operating in the visible-to-near-UV bands (300-900 um) that is designed to achieve 20 milliarcsecond image stability over a 0.5 degree field-of-view for integration periods ranging from 10-30 minutes, where it is estimated that a 900 second exposure on SuperBIT can resolve point sources of magnitude 24 at the 10? level. As such, SuperBIT is well suited for weak lensing experiments of galaxy clusters over high redshifts that require high image resolution over a wide field of view, and for other proposed experiments related to solar planet spectroscopy and exoplanet studies. The design, implementation, and flight performance to-date of the attitude determination and control systems (ADCS) for SuperBIT are the focus of this work, where emphasis is placed on mitigating and, in fact, exploiting the sub-orbital disturbance environment driven by compound pendulation and other stratospheric effects. The ADCS architecture is designed for real-time, high-gain feedback to compensate for sub-orbital disturbances down to 1-2" at the telescope level in addition to a high bandwidth piezoelectric tip-tilt actuator that removes any remaining disturbances on the focal plane down to 0.02". Furthermore, design methodologies from spacecraft dynamics and control are implemented to emphasize control robustness and autonomy from the stratosphere. Performance from the first test 8 hour test flight from Timmins, Ontario in September 2015 is presented here, where subarcsecond performance is demonstrated at the telescope level and at the science camera focal plane over hour long tracking periods. Current work and progress to-date in preparation for the fully operational three month flight of SuperBIT from New Zealand in 2018 is discussed within the context proposed of astronomical and cosmological experiments.

9906-64, Session 17

Pointing and control system performance and improvement strategies for the SOFIA Airborne Telescope

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The Stratospheric Observatory for Infrared Astronomy (SOFIA) has already successfully conducted over 240 flights. In its early science phase, SOFIA's pointing requirements and especially the image jitter requirements of less than 1 arcsec rms have driven the design of the control system.

Since the first observation flights, the image jitter has been gradually reduced by various control mechanisms. The resulting current control structure consists of two parts, the rigid body attitude control system and a feed forward based compensator of flexible telescope deformation (so-called Flexible Body Compensation system, FBC). The rigid body control loop is based on fiber-optic gyros as well as on three tracking cameras. Additionally, the FBC feeds accelerometer data through fixed-gain filters to the secondary mirror for compensation. This system allows us to achieve the standards set for early science on SOFIA.

Notably, the increasing demands on the image size require an image jitter of less than 0.4 arcsec rms to reach SOFIA's scientific goals. The major portion of the remaining image motion is caused by deformation and excitation of the telescope structure in a wide range of frequencies due to aircraft motion and aero-acoustic effects.

Thorough testing of the current system under various flight conditions have revealed a variety of opportunities for dramatic improvements. The currently applied filters have solely been developed based on a FEM analysis. By implementing the inflight measurements in a simulation and optimization, an improved fixed-gain compensation method was identified. After implementing the new filter, jitter measurements with up to 400 Hz sampling frequency using the fast imaging tracking camera show promising results and will be discussed in this paper.

Flight data analysis indicates that the currently used sensors for the FBC are one of the bottlenecks, as they do not measure all relevant Eigenmodes of the telescope. In addition, the implemented filters cannot optimally estimate the image motion. This leads to the necessity of new strategies for compensation, especially in bumpy flight conditions. This issue will be addressed in this paper.

The precisely balanced interaction of both control parts is crucial to achieve unprecedented image quality. With the changes in the FBC the assigned responsibilities in both control loops has to be revisited and will be discussed.

9906-65, Session 18

A high-sensitivity EM-CCD camera for the open port telescope cavity of SOFIA

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The Stratospheric Observatory for Infrared Astronomy (SOFIA) has three target acquisition and tracking cameras. All three imagers originally used the same cameras, which did not meet the sensitivity requirements, due to low quantum efficiency (QE) and high dark current. The Focal Plane Imager (FPI) suffered the most from high dark current, since it operated in the aircraft cabin at room temperatures without active cooling. In early 2013 the FPI was upgraded with an iXon3 888 from Andor Techonolgy. Compared to the original cameras, the iXon3 has a factor five higher QE, thanks to its back-illuminated sensor, and orders of magnitude lower dark current, due to a thermo-electric cooler and "inverted mode operation". This leads to an increase in sensitivity of about five stellar magnitudes.

The Wide Field Imager (WFI) and Fine Field Imager (FFI) shall now be upgraded with equally sensitive cameras. However, they are exposed to stratospheric conditions in flight (typical conditions: T ≈ -40°C, p ≈ 0.1 atm) and there are no off-the-shelf CCD cameras with the performance of an iXon3, suited for these conditions. Therefore, Andor Technology and the Deutsches SOFIA Institut (DSI) are jointly developing and qualifying a camera for these conditions, based on the iXon3 888. These changes include replacement on electrical components with Mil-Spec components and various system optimizations, a new data interface that allows the image data transmission over ~30 m of cable from the camera to the controller, a new power converter in the camera to generate all necessary operating voltages of the camera locally and a new housing that fulfills airworthiness requirements.

A prototype of this camera has been built and tested in an environmental test chamber at temperatures down to T = -62°C and pressure equivalent

to 50,000 ft altitude. In this paper, we will report about the development of the camera and present results from the environmental testing.

9906-66, Session 18

SOFIA design history: optics, structure, and mechanics

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The paper describes the development of the optical subsystem, the telescopes structure, the telescope mount and the interface to the aircraft from the conceptual design up to the finally as-built telescope and comments their influence on the overall observatory performance.

9906-67, Session 19

A feasibility study for airborne calibration of the Cherenkov Telescope Array

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Currently in its pre-construction phase, the Cherenkov Telescope Array (CTA) will be the next generation very high energy gamma-ray observatory. CTA is designed to achieve an order of magnitude improvement in sensitivity, a much wider energy coverage and greatly improved energy and angular resolution compared to the current imaging atmospheric Cherenkov telescope facilities. To achieve these ambitious goals, CTA will comprise three telescope size classes: Small (SST), Medium (MST) and Large (LST). Operating an array of different telescope sizes introduces significant challenges, particularly with regard to cross-calibration. Accurately characterising the different optical throughput of the individual telescopes is helped if a common known calibration light source can be used.

To achieve all-sky coverage, the CTA observatory will consist of two arrays, one in each hemisphere. The northern array will contain approximately 20 telescopes (LSTs and MSTs) spread over about 1 km2, while the southern array will contain over 100 telescopes (LSTs, MSTs and SSTs) spread over an area of a few square kilometers. For practical reasons, IACTs are generally exposed instruments and thus subject to the effects of weathering, which contribute to the degradation of the telescopes' optical systems. To determine this degradation, we must calibrate the optical throughput of the individual CTA telescopes. To meet the CTA requirements on systematic uncertainties means determining the wavelength-dependency of the optical throughput, thus motivates the periodic use of a multi-wavelength-capable calibration light source to monitor the optical throughput of each individual CTA telescope.

The advances in battery life, flight control software and carbon fibre technology over recent years have made the use of small unmanned aerial vehicles (UAVs) as an airborne calibration platform for astronomical facilities a possibility. Early work by the Pierre Auger and Telescope Array cosmic ray detectors took advantage of these advances to use UAVs to calibrate their fluorescence telescopes. CTA will take advantage of this possibility of using UAVs as the basis of an airborne calibration system. While the primary purpose of an airborne calibration system for CTA would be the cross-calibration of different telescope types and the monitoring of the multi-wavelength performance of CTA telescopes' optical throughput, the versatility of the UAV platform allows for a wide variety of calibration and monitoring procedures to be performed, such as the mapping the atmospheric dust content above the array.

As part of CTA's efforts to realising the possibility of an airborne calibration system, we have recently completed a feasibility study to use a UAV to cross-calibrate the relative sensitivity of the CTA telescopes for the current array designs. In this contribution, the cross-calibrating performance of an airborne calibration device is described, together with the ongoing work to characterise the flight performance of a UAV carrying the calibration payload.

9906-68, Session 19

Low cost multi-purpose balloon-borne platform for wide-field imaging and video observation

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Atmosphere layers, especially the troposphere, hinder the astronomical observation. For more than 100 years astronomers have tried observing from balloons to avoid turbulence and extinction. New developments in card-size computers, RF equipment and satellite navigation have democratised the access to the stratosphere.

As a result of a ProAm collaboration with the Daedalus Team we have developed a low-cost multi-purpose platform with stratospheric balloons carrying up to 3 kg of scientific payload. The Daedalus Team is an amateur group that has been launching sounding probes since 2010. Since then the first two authors have provided scientific payloads for nighttime flights with the purpose of technology demonstration for astronomical observation.

It is a passive craft, with basic stabilisation and 2-hour length nominal mission. Current design has up to 4 observational ports, three at the sides of the square-shaped probe and one aiming at nadir for Earth Observation. The probe uses one or two meteorological sounding balloons to get out of the troposphere. The probe usually rises to 30km of altitude and then falls free with a parachute. The probe has GSM, RF and GPS beacons and some missions had also bidirectional communication. During the flight the probe is chased from ground using the beacons in order for recovery as all the data is stored inside.

The first of these flights was in 2010 as an instrumental test to monitor light. The same year a second flight over the city of Jaén successfully took the first images for scientific use. In 2014 the project was repeated over the city of Madrid, acquiring images of quality comparable to the ones from airborne instruments with a hundredth of the cost.

The other scientific objective of these night flights is the estimation of meteoroid influx at Earth through the observation of meteor showers. Observing meteors from the stratosphere improves detection efficiency thanks to much lower extinction and less background brightness. Other teams had already demonstrated the benefits of airborne observations for these objects. In 2011 the team sent a low-light video camera to observe the Draconids 2011 outburst. Unfortunately the recording system failed and then mission had to be redesigned. For Geminids 2012, Camelopardalids 2014 and Geminids 2015 the instruments have worked flawlessly and the data are under analysis. Imaging and video devices with broad-band filters have been employed and results are comparable with airborne and satellite products, especially for high-resolution images.

9906-69, Session 19

Optical design for the large balloon reflector

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Balloon-borne telescopes have enabled terahertz observations of astrophysical objects which would otherwise be blocked or severely attenuated by the Earth's atmosphere. Successful missions such as BLAST (Balloon-borne Large Aperture Sub-millimeter Telescope) and now STO (Stratospheric THz Observatory) have proven that hanging a telescope from a balloon is a very economical approach for terahertz astronomy compared to the cost of flying space-borne instruments.

Nevertheless, one of the drawbacks is the ultimate pointing accuracy of the hanging telescope, which restricts the use of large apertures at very high frequencies.

A new concept, the Large Balloon Reflector (LBR) has been proposed and funded through the NASA Innovative Advanced Concepts (NIAC) program. In this approach the main reflector of the telescope is the metalized hemisphere of a smaller spherical balloon, 5 to 20 m in diameter, inflated inside the much larger carrier balloon. A spherical corrector optics and terahertz receiver sit in the interior of the sphere. The initial astrophysical targets of interest are the spectral lines of water at 557 GHz and Lithium at 444 GHz associated with star formation and Hi-z galaxies.

We will present the details of the optical design, corrector system, mechanical layout, tolerances, pointing requirements, and overall performance of LBR.

9906-70, Session 20

Telescope performance and results from the KMTNet 1.6 meter project completion

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The KMTNet telescope Project, sponsored by The Korea Astronomy and Space Science Institute (KASI), commissioned three wide-field equatorial mount telescopes of 1.6 meter aperture in 2015, and all three are now fully operational. The mission of this project is to conduct continuous observations of the Galactic bulge region to search for extra-solar planets. Southern latitude sites where installation of these telescopes is now complete include SAAO (South Africa), CTIO (Chile), and SSO (Australia). A prime-focus configuration, along with a three-lens coma corrector achieves the 2.8 degree diagonal FOV, and a fourth lens serves both as a detector dewar window and field-flattener. Four spectral filters are selectable remotely, and a variable-speed shutter is located at the corrector assembly. The basic mechanical design utilizes a scaled-up version of the successful 2MASS Telescopes built by the authors in the late 1990's. The efficient method for installation at the sites is described, typically 5 weeks of on-site work per site. Enclosures and fully operational domes were in place preceding each telescope installation that were identical to the Tucson, Arizona test facility, making the fit-up both efficient and quickly successful. Collimation and final optical adjustment was straightforward and resulted in star images better than 0.8 arcseconds in the astronomical "I" band (local seeing limited). Absolute pointing accuracy is 8 arcseconds above 60º from zenith. The flexure-style focus mechanism, driven by three precision actuators, moves the entire headring assembly and provides real-time focus capability along with tip/tilt, and active primary mirror cooling was successfully implemented for the Zerodur primary to prepare it for nighttime thermal conditions at each observatory. An extensive testing and verification program following installation shows that performance of mechanical and optical systems is to specification for the project. Initial optical performance was verified using small cameras placed at various positions in the focal plane. Later tests using the final science cameras shows that this method was effective in spot-checking the image at the focal plane. One critical factor in the rapid installation and first light at each site was assembling each telescope and enclosure in our test facility in Tucson, AZ prior to shipping the hardware. This method verified observatory interfaces tracking, optical characteristics at various attitudes, and overall observatory functionality. Mount manipulation, using T-Point® and star positions was well within adjustments provided for East-West rotations as well as declination axis angle. The three science cameras, fabricated by The Ohio State University Department of Astronomy, Imaging Sciences Laboratory (ISL), are now installed and are operational at each site. A significant performance achievement is the one-hour tracking accuracy in right ascension of 0.05 arcseconds, reducing the necessity for star-offset guiding under many circumstances. A review of the final mechanical and optical design are presented, along with the testing protocols, and detailed results of telescope optical and mechanical performance.

9906-71, Session 20

Customized overhead cranes for installation of India's largest 3.6m optical telescope at Devasthal, Nainital, India

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India's largest 3.6m optical telescope has been recently installed at Devasthal site of Aryabhatta Research Institute of Observation Sciences (ARIES), an autonomous Institute under Department of Science and Technology, Government of India. Devasthal (29o 21'N, 79o 41'E), a prime astronomical site at an altitude of about 2450m above mean sea level is located in Kumaon region of Uttarakhand, India. The 3.6m modern technology telescope with active optics was designed, manufactured, factory tested and supplied to ARIES by Advanced Mechanical and Optical Systems (AMOS), Belgium. A steel building with rotating cylindrical steel dome was erected to house telescope and its accessories in its dome and supporting structure while mirror aluminizing plant was installed in the extended part of building at hilltop of Devasthal site. Customized overhead cranes were essentially required inside the telescope building as their were space constraints around the building for operating big external heavy duty cranes from outside, transportation constraints in route for bringing heavy weight cranes, altitude of observatory and sharp bends etc. to Devasthal site. To meet the challenge of telescope installation from inside the telescope building by lifting components through its 5.5m x 5.5m hatch opening, two single girder cranes and two under slung cranes of 10 ton capacity each were specifically designed, developed and installed by ARIES in consultation with Precision Precast Solutions (PPS), Pune India. All the four overhead cranes were custom built to specifically achieve the goal of handling telescope mirrors and its various components during telescope integration. Cranes were manufactured at Indiana Machine Tools (IMT), Gobindgarh, India and factory tested to meet AMOS requirements of telescope installation. Two customized single girder cranes of 10 ton capacity each were installed in extended building with a span of 11.15m and bay length of 24m whereas, two more customized 10 ton capacity under slung cranes were installed in dome building with a span of 4.9m and bay length of 14.7m. Cranes were installed in limited available space inside the building and tested as per IS 3177 using specifically prepared dummy loads to ensure safety of telescope components and its delicate mirror during installation and assembly. Apart from important contribution of cranes in successful integration of mechanical, optical and electrical components of telescope by AMOS, they also served in installation of mirror aluminizing plant, first aluminization of 3.7m diameter primary mirror of telescope, refurbishing activities and in various other maintenance activities. Cranes were specifically equipped with many features like VVVFD compatibility, provision for tandem operation with encoders, digital load display, anti-collision mechanism, electrical interlocks, radio remote, low hook height and compact carriage etc. Single girder cranes are capable of hoisting at very slow speed of the order of 3.3 mm/s and under slung cranes at about 5.8 mm/s for precise installation of fragile telescope mirror, various heavy

critical telescope components and during mirror aluminizing activities etc. Present paper presents design, development and testing of four customized overhead cranes and their vital role in successful installation of 3.6m telescope over its eccentric pier inside the building.

9906-72, Session 20

Status and performance of Lowell Observatory's Discovery Channel Telescope in its first year of full science operations

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Lowell Observatory's Discovery Channel Telescope (DCT) is a 4.3-m telescope designed and constructed for optical and near infrared astronomical observation. The DCT is equipped with a cube capable of carrying five instruments along with the wave front sensing and guider systems at the f/6.1 RC focus. The facility formally finished commissioning at the end of 2014. In 2015 the DCT ran in full science operations mode. This report addresses operational methods, instrumentation integration and the performance of the facility as determined from delivered science data, lessons learned and plans for future work and instruments.

9906-73, Session 20

Current status of the facility instrumentation suite at the Large Binocular Telescope Observatory

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The current status of the facility instrumentation for the Large Binocular Tele-scope (LBT) is reviewed. The LBT consists of two 8.4 m primary mirrors and fully adaptive f/15 Gregorian secondary mirrors on a single mount yielding an effective collecting area of 11.8 m and an interferometric baseline of up to 23 m. The three facility instruments at the LBT include: 1) the Large Binocular Camera (LBC), a pair of blue and red optimized optical CCD imagers mounted at the prime foci each telescope with a 23'x25' field of view (FOV). The available filter suite covers the 0.3-1.1 ?m region, including the addition of new medium-band filters centered on TiO (0.78 ?m) and CN (0.82 ?m) for stellar population studies; 2) the Multi-Object Double Spectrograph (MODS), a pair of identical optical spectrographs mounted at the straight through f/15 Gregorian focus of each telescope. The capabilities of MODS include imaging with SDSS filters (u, g, r, i, and z) and medium resolution (R ~ 2000) or low resolution prism (R~200-500) spectroscopy with 24 inter-changeable masks (multi-object or long-slit) over a 6'x6' FOV. Each MODS is capable of individual blue (0.32-0.6 ?m) and red (0.5-1.05 ?m) spectroscopic coverage or both instruments can employ a dichroic beam splitter for 0.32-1.05 ?m wavelength coverage in a single exposure; and 3) the two LBT NIR Spectroscopic Utility with Camera Instruments (LUCI), mounted at each bent-front Gregorian f/15 foci and accessible by a rotating tertiary mirror. LUCI is designed for seeing-limited (4' x 4' FOV) and diffraction-limited (0.5' x 0.5' FOV) imaging and spectroscopy over the wavelength range of 0.95-2.5 ?m with spectroscopic resolutions of 400 ? R ? 20,000. The spectroscopic capabilities include 32 interchangeable multi-object or long-slit masks which are cryogenically cooled.

Recently, LUCI1 was upgraded to include a new detector with better quantum efficiency; to install a high-resolution camera to best utilize the exceptional image quality afforded by the adaptive optics system; and to install a grating designed primarily for use with the adaptive optics system. Thus, like MODS both LUCI instruments now have nearly identical imaging and spectroscopic configurations and as well as performance. The software interface for LUCI has also been replaced, allowing both instruments to be run together from a single user interface.

Although both primary mirrors reside on a single fixed mount, they are capable of operating as independent entities within a defined "co-pointing" limit. This provides users with the additional capability to independently dither each mirror or center observations on two different sets of spatial coordinates within this limit. With the installation of the facility instruments now complete, we also report on the first science use of "mixed-mode'' operations, defined as the combination of different paired instruments with each mirror (i.e. LBC+MODS, LBC+LUCI, LUCI+MODS).

9906-74, Session 20

Completion of the 3.6m Devasthal Optical Telescope project and the first results

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The 3.6 meter Devasthal Optical Telescope (DOT) Project was initiated bythe Aryabhatta Research Institute of Observational Sciences, Nainital, India, in 2007 with a partnership with Belgium. Recently, the telescope has been successfully installed and commissioned at Devasthal. The telescope site, Devasthal was chosen after carrying out extensive surveys in the Kumaun regions of central Himalayas. Devasthal is a low-wind good photometric astronomical site with a measured ground-level median seeing of about one arc sec. The location of this telescope assumes global importance for observing transient celestial objects since it is located in the middle of crucial longitudinal gap between the locations of 4-m class global optical telescope observing facilities in Australia in East and the Canary Islands in West. The primary goals of the 3.6m DOT is to carry out seeing-limited photometric imaging and the high resolution spectral observations at visible and near-infrared wavelengths.

The telescope manufacturing was contracted to a Belgian Company named Advanced Mechanical and Optical Systems (AMOS). The telescope has Ritchey-Chretien optics, alt-azimuth mount, active control of primary and a field-of-view of 30 arc min at the Cassegrain focus. The telescope enclosure, aluminizing and other auxiliary facilities were designed and built in India. The building was completed in June 2014. The building houses the concrete pier, the telescope, four overhead-cranes and a 3.7 m mirror coating plant. Considering the limited available space at site, a very compact telescope enclosure was designed in which the telescope pier is off-centered. The assembly and integration of entire telescope has been completed inside the enclosure. The primary mirror of telescope is mounted about 15m above the ground, where the contribution from ground level seeing is expected to be less than 0.5 arc sec. The telescope floor level is at 11m and a total of 12 ventilation fans are installed on dome-support enclosure for thermalisation of telescope before start of observations. The primary mirror of the telescope was coated with Aluminium for the first time using on site coating facility at Devasthal before its integration into the telescope. The design and implementation of synchronization of dome with the telescope has also been successfully

achieved. The first engineering light with the telescope was obtained on 22nd March 2015.

The on-sky performance of telescope has been tested with CCD camera and wave-front-sensor during March to December 2015. The measured pointing accuracy of the telescope is 2 arc sec RMS and the tracking accuracy is better than 0.1 arc sec RMS in an hour. Test images were recorded using a 4kx4k Imager as first light instrument. The binary stars with separation down to 0.4 arc sec have been clearly resolved implying that seeing at site is close to what was expected during site characterizations. In this contribution, a brief overview and status of installation activities at site and preliminary on-sky test results is presented.

9906-207, Session PS11

Smart co-phasing system for segmented mirror telescopes

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One of the main challenging tasks in nowadays segmented mirror telescopes is to perform an efficient co-phasing of the sub-apertures. The dynamic range of such a co-phasing starts from several tenths of micrometers corresponding to the mechanical accuracy to a few nanometers required for the piston and tip/tilt corrections. A system able to perform the complete co-phasing task of a telescope made of maximum seven sub-apertures is described. The system needs basic hardware and is relatively simple to implement. Coarse and fine measure technics are first addressed. The proposed setup is then presented. It is divided into three sub-systems: Coarse phasing, Fine phasing and Locking feedback system. The guide lines to improve the system speed and to increase the number of sub-apertures are evaluated.

First, the coarse sensor records the Point Spread Function (PSF) in the focal plane of the telescope by means of a CCD. Then, calculates the piston with the inverse of the Gaussian function that is proportional to the coherence level of the PSF. The coherence level is linked to the Modulation Transfer Function (MTF).

The coarse sensor measures piston between three different ranges (3 filters) that are overlapped in their limits in order to cover a range from 160µm to 100nm.

After the coarse measurement, an actuator moves the mirror by a distance equals to the measured error in order to correct it. This actuator has a range of 400µm and a resolution of 4nm.

The fine phasing system has a measurement range of +/- 310nm and is able to correct piston and tip/tilt errors. The fine piston error is proportional to the peak height in the OTF phase component, i.e. the phase transfer function (PTF). These piston error are calculated by multiplying the height of the peaks by a constant. The fine tip/tilt errors are proportional to the inclination of the top of the peaks of the PTF. These tip/tilt errors are then calculated by measuring the derivate of the top of the peaks and multiplying it by a constant. The actuator corrects then the measured fine errors.

Once the fine tuning achieved, the system needs to stay co-phased. A locking feedback system is used to maintain the piston and tip/tilt errors smaller than 10nm and 1 arcsec. It consists in a control algorithm that measures the errors 3 times per second in order to correct them in real time. By this way a diffraction limited segmented telescope can be realized.

The speed of the system can be improved with a capacitive locking feedback system. This can be achieved with capacitive sensors that are very fast (several hundreds of times per second) and precise (nm scale) but they shall be calibrated before utilization. The fine sensor is then be used for calibration before the turn ON of the capacitive feedback locking system. The quantity of segments can be increased with a dynamic mask. This can be realized with a LCD (liquid crystal display) system. With the dynamic mask, it will be possible to co-phase infinite sub-pupil quantity (7 each time).

9906-208, Session PS11

SOAR Telescope seismic performance II: seismic mitigation

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We describe design modifications to the SOAR telescope intended to reduce the impact of future major earthquakes, based on the facility's experience during recent events, most notably the September 2015 Illapel earthquake. Specific modifications include a redesign of the encoder systems for both azimuth and elevation, seismic trigger for the emergency stop system, and additional protections for the telescope secondary mirror system. The secondary mirror protection may combine measures to reduce amplification of seismic vibration and "fail-safe" components within the assembly. The status of these upgrades is presented.

9906-209, Session PS12

Glycol leak detection system

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SALT, the Southern African Large Telescope, consists of many subsystems that require cooling and was accomplished by using Ethelyne glycol coolant throughout the telescope. The risk of glycol pipes leaking and potentially causing damage to not only electrical equipment and instruments, but also to the primary mirror, was identified and needed to be addressed. Damage to equipment could result in science downtime for up to a year. A study was conducted to determine the best way of detecting a glycol leak. The first concept, which is explained in Sec. 1, was to use differential pressure readings between Supply and Return glycol pipes and trigger the system when this resulted in in a difference larger than a predefined setpoint. The second accepted concept which is in operation is the use of leaf wetness sensors and is also explained.

1 . Differential Pressure Controlled Detection

The first concept was to use differential pressure readings between the glycol supply and return line. This would require pressure transmitters on both lines been monitored by a micro controller. On power up, the controller would initialize whereby average pressure is calculated over a 60 second period on both sensors. After this period the controller would switch to ready mode and would continue to monitor the pressure readings. If the difference between the supply and return pressure readings become greater than averaged limits, the valve on the supply side would close and the alarm relay would activate. The controller would be manually reset by the technician after checks are performed. On ground level, this system worked without any problems where the pressure readings are stable and between 1.4 and 2.1 Bar. The pressure on each line would not vary more than 0.3 Bar and the pressure difference between the supply and return would not vary more than 0.5 Bar.

The system was tested on payload level which is over 20 meters above ground level and retested. Due to the various splits and height of the glycol pipes, the pressure readings had given different results, and was found to be very erratic causing the system to not find a suitable differential reading to operate from. The return pressure would give readings of 0 to -1 bar and supply would be between 1 and 2 bar. This tolerance would be too large and unreliable to be used to determine whether there is a leak in the pipe

or not and would only be suitable for a pipe burst. We needed glycol to be detected on its early stages of a leak.

2. Leaf Wetness Sensor Controlled Detection

The second concept which was tested was to rely solely on leaf wetness sensors. These sensors made of a PC board with a fork design copper track is plugged into a controller. This would trigger if the resistance between the tracks become smaller than a preset amount. These sensors would be placed in various critical areas around the payload where leaks are more likely to occur. The controller would respond as with the previous concept would, when triggered, would close the valve and could only be reset if the alarm is cleared. The alarm is in a cleared state when the sensor is replaced and free from glycol.

The final concept is tested as part of our maintenance tasks and is currently performing as required.

9906-210, Session PS12

The MROI Array telescopes: the relocatable enclosure domes

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The MROI - Magdalena Ridge Interferometer is a project which comprises an array of up to 10 1.4m diameter mirror telescopes arranged in a “Y” configuration. Each of these telescopes will be housed inside a Unit Telescope Enclosure (UTE) which are relocatable onto any of 28 stations.

EIE GROUP Srl, Venice – Italy, was awarded the contract for the design, the construction and the erection on site of the MROI by the New Mexico Institute of Mining and Technology.

The close-pack array of the MROI - including all 10 telescopes, several of which are at a relative distance of less than 8m center to center from each other - necessitated an original design for the Unit Telescope Enclosure (UTE). This innovative design enclosure incorporates an unique dome/observing aperture system to be able to operate in the harsh environmental conditions encountered at an altitude of 10,460ft (3,188m).

The main characteristics of this Relocatable Enclosure Dome are: a Light insulated Steel Structure with a dome made of composites materials (e.g. glass/carbon fibres, sandwich panels etc.), an aperture motorized system for observation, a series of louvers for ventilation, a series of electrical and plants installations and relevant auxiliary equipment.

The first Enclosure Dome is now under construction and the completion of the mounting on site id envisaged by the end of 2016.

The Project includes a relocation systems with a rail based system, wheels fixed to the bottom of the enclosure and various lifting mechanisms. The relocation system utilizes a modified reachstacker (a transporter used to handle freight containers) capable of manoeuvring between and around the enclosures, capable of lifting the combined weight of the enclosure with the telescope (40tons), and can manoeuvre the enclosure with minimal vibrations.

9906-211, Session PS12

SOAR Telescope seismic performance: impact of the 2015 Illapel earthquake

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The response of the SOAR telescope to the September 2015 Illapel earthquake is documented and placed in the context of other recent, nearby seismic events. Accelerometer data collected on the telescope during these events suggest that observed intensities due to events occurring to the south of the SOAR telescope site are higher than predicted by simple models. Amplification of accelerations occurs at several places within the telescope system, most notably the telescope top end and secondary mirror assembly, and the azimuth encoder system. Damage in these areas is described, and an overview of the earthquake recovery effort is presented.

9906-216, Session PS13

The GCT camera for the Cherenkov Telescope Array

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The Cherenkov Telescope Array (CTA) is the next generation ground-based imaging atmospheric Cherenkov telescope (IACT) array and will operate as an Observatory. Building on the strengths of current IACTs, CTA is designed to achieve an order of magnitude improvement in sensitivity, with unprecedented energy and angular resolution. Importantly, CTA will also increase the energy reach of ground-based gamma-ray astronomy, from ~0.02 TeV to beyond 100 TeV.

To meet these ambitious goals, CTA will consist of three telescope classes: Small, Medium and Large Sized Telescopes (SST, MST and LST respectively). To achieve all-sky coverage, CTA will consist of two arrays, one in each hemisphere. The northern array will contain approximately 20 telescopes spread over about 1 km2, while the southern array will contain over 100 telescopes spread over an area of several square kilometers.

The Gamma-ray Cherenkov Telescope (GCT) is a dual-mirror SST prototype proposed for CTA. The dual-mirror optical design allows reduction of the telescope's plate scale, enabling small form-factor photosensor elements to be used in the camera. Additionally, the good off-axis point spread function allows a large field-of-view camera to be built from these photosensors. There are two prototypes for the GCT camera: one based on multi-anode photomultipliers (CHEC-M) and one based on silicon photomultipliers (CHEC-S). Both of these prototypes contain 32 modules, totalling 2048 pixels. During event read out, the analogue signal from each pixel is pre-amplified before being passed to the camera front-end electronics modules. These modules digitise the signal and read out the full waveform of each pixel, for every event triggering the camera. In total there are 32 camera modules, with each camera module containing four custom TARGET ASICs. The use of ASICs in the camera module affords the GCT fast data readout, with a large amount of flexibility. This allows for optimisation of the event read-out window, buffering of triggered events and variations in the resolution which the event waveforms are sampled.

The first GCT prototype camera (CHEC-M) was recently been commissioned, with on-telescope tests taking place at the Paris Observatory, Meudon, on the prototype telescope. The culmination of the commissioning is the recording of the first Cherenkov images from a SC telescope, and the first Cherenkov images recorded by a CTA prototype. In this contribution we give a detailed description of the GCT camera and present preliminary results from CHEC-M tests.

9906-218, Session PS13

Challenges for QTT structure

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An amazing radio telescope called QTT (the short form of QiTai radio Telescope) will be constructed in Qitai County, Xinjiang, China. QTT is a 110-m aperture fully steerable radio telescope with zenith range about 83o, reaching 11o south of the Galactic center and its observing frequency range covers from 150MHz-115GHz. The main reflector surface accuracy achieves 0.2mm (rms) after long term adjustment, and the sub-reflector surface accuracy is 0.07mm (rms) while the pointing accuracy is less than 2.5arcs above 6mm observation wave length. The application goal accords with the demands of Chinese deep space exploration, to satisfy the Chinese strategic plan and to make a good preparation for Chinese technology and science.

Anyhow for an antenna like QTT will meet many challenges for its structure design. Here we will introduction the structure problems we meet including: antenna weight vs. stiffness, azimuth track, alidade, reflector panel, reflector and alidade connecting, actuator, feeds switching, sensor use, etc. and show the current progress.

9906-220, Session PS13

Status of the Trans-Neptunian Automated Occultation Survey (TAOS II)

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The Transneptunian Automated Occultation Survey (TAOS~II) will aim to detect occultations of stars by small (sim1~km diameter) objects in the outer Solar System. Such events are very rare ($<10^{-3}$ events per star per year) and short in duration (sim200~ms), so many stars must be monitored at a high readout cadence. TAOS~II will operate three 1.3~meter telescopes at the Observatorio Astron'{o}mico Nacional at San Pedro M'{a}rtir in Baja California, M'{e}xico. With a 2.3~square degree field of view and high speed cameras comprising CMOS imagers, the survey will monitor 10,000~stars simultaneously with all three telescopes at a readout cadence of 20~Hz. Construction of the site began in the fall of 2013. This poster will present the status of the survey infrastructure and future plans for the completion of the site development and telescope installation.

9906-221, Session PS13

Characterizing the vibration environments of the Gemini telescopes

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We report the results of a multi-year program to measure the vibration characteristics of the two Gemini telescopes, evaluate the effect of vibrations on image quality, and implement solutions to mitigate some of the vibrations. At Gemini North, the investigation was motivated by frequent instances of elongated and irregular images, particularly when conducting adaptive optics observations. Wavefront sensor data at 200 Hz frame rate revealed a principal source of image degradation to be a 12

Hz periodic oscillation induced by the GNIRS instrument cryocoolers that was strongest at a specific angle of the Cassegrain Rotator. To investigate the oscillation further, the telescope was outfitted with a network of accelerometers on both the primary (M1) and secondary (M2) mirrors and their support systems. The accelerometers revealed harmonics from all the instrument cryocoolers throughout the telescope, but the 12 Hz oscillation was specifically detected in M1 and its cell. The relative phases measured across M1 showed the mirror to be oscillating in tilt with an amplitude sufficient to cause the image motion measured by the WFS. Detailed FEA analysis of the mirror cell and its support system corroborate the hypothesis that the cryocoolers excite a resonance near 12 Hz, producing the optical oscillation. In mid-2014, a real-time vibration tracking algorithm was added to the M2 fast-guiding system to compensate the 12 Hz oscillation. At Gemini South, a simpler accelerometer network was implemented to study image oscillations reported by GPI. A similar analysis indicated that the GPI cryocoolers were injecting a 60 Hz oscillation into M1, in this case impulsing the center of the mirror to cause an aberration similar to defocus. Attempts to compensate the oscillation within GPI and add passive vibration dampers were only partially successful, but in 2015 an active cancellation system installed on the cryocoolers substantially reduced the vibration level. We also identified and suppressed additional sources of vibration affecting both GPI and the GeMS AO system. Our work demonstrates the importance of monitoring the vibration environment of modern telescopes, in particular when using adaptive optics to achieve diffraction-limited image quality.

9906-212, Session PS14

Performance evaluation method on Antarctic survey telescopes

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Antarctic Survey Telescopes deployed to Dome A, Antarctica are less-intrusive during observation for its unattended and automatic design. So it is important to evaluate the performance of control system automatically. The analysis trees are constructed to get the performance evaluation result of the control system based on the data from the collection system. The result was used to help determine when to adjust and optimize the system and how to maintenance the equipment in next expedition.

9906-213, Session PS14

Experience with the operation of the European ALMA antennas

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The 25 European antennas of ALMA were delivered by ESO to the ALMA project in Chile between April 2011 and September 2013. Since then they have been in operation without substantial problems. Their combined time of operation is already significant and allows us to draw conclusions regarding their ability to fulfill the original specification, in terms of both scientific performance and operational availability. This latter aspect is of central importance for the ALMA observatory, which has to operate and be routinely maintained at 5000m. In this paper, we will summarize the experience gained during the past five years of operation. We will characterize the performance of the antennas in routine operation and compare with the data obtained during acceptance testing. We will also describe the few technical issues experienced while operating at 5000m and the way in which these were treated during these first years of operation. We will evaluate the effective reliability obtained in service based on field data and draw some conclusions as to the way in which reliability and maintainability aspects were covered during the process which led to the final design of the antenna. We will discuss the smart use of software to handle redundancy in a flexible way and to exclude failed components without affecting overall antenna operability. This approach is based on remote access to the antennas, which is routinely used to read the status and to control modes of the Antenna Control Unit. The use of low- level diagnostics enabled by remote access allows us to shorten the trouble- shooting cycle and to optimize physical interventions on the antennas, which are sometimes located far from the centre of the ALMA array. Finally, the paper will cover the maintenance manuals delivered by ESO with the antennas, which were produced using an industrial interactive standard. It will be explained why this advanced and innovative concept has not achieved the success that was expected, and why the traditional form is preferred at the ALMA Observatory.

9906-214, Session PS14

The LLAMA Observatory: a new sub-mm facility for Latin America

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The Large Latin American Millimeter Array (LLAMA) is a joint scientific and technological undertaking of Argentina and Brazil whose final goal is to install and operate a submm array. As a first step one antenna will be constructed and operated in a single dish mode and as an element of a VLBI observatory in Latin American network that may include ALMA, APEX, LMT and ASTE and participate in the Event Horizon Telescope (EHT). The antenna will be located in the Argentinean High Andes, at Cerro Alto Chorrillos, at an altitude of 4800 meters, 180 km south-east of ALMA, with atmospheric conditions similar to those for ALMA. It is located 20 km from the town of San Antonio de los Cobres from where remote operations will take place. The antenna will be assembled in the second half of 2016, followed by commissioning and operations will start in 2017.

LLAMA is to have a North American ALMA-type antenna, constructed by VERTEX, complemented with two Nasmyth cabins equipped with 6 ALMA-like receiver cartridges in two cryostats. The Cassegrain focus area will be used for a bolometric camera or a heterodyne array receiver but it will contain a beam re- distribution optics to the two Nasmyth cabins. The novel design allows simultaneous observations between two receiver bands in both polarizations and between four bands in one polarization.

The LLAMA antenna is, as for ALMA, suitable for solar observations and will be unique for its capability to make simultaneous observations in 4 bands. This is also of interest for (sub-)mm VLBI observations as has been demonstrated with the Korean VLB array. LLAMA is planned to participate in the Event Horizon Telescope.

The First Light equipment will include a band-5 and a band-9 receiver.

The LLAMA is one of the first observatories to take advantage of the open ALMA Common Software package for its software development. This facilitates considerably the software development effort for equipment monitor and control.

9906-215, Session PS14

Power supply system design and build for Antarctica telescope

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Currently, more and more telescopes were built and installed in Dome A of Antarctic. The telescopes are remote controlled, unattended operation due to Dome A's environment. These telescopes must be work successfully at least one year without any failure. According to past experience, the power supply system is the weakest point in whole system. The telescopes have to stop if the power system have a problem, even a minor problem. So the high requirement for power supply system are presented. The requirement include high reliability, the self-diagnosis and perfect monitor system. Furthermore, the optic telescope only can work at night. The power source mainly relay on diesel engine. To protect the Antarctic environment and increase the life of engines. The power capacity is limited during observation. So it need the power supply system must be high power factor, high efficient. To meet these requirement, one power supply system was design and built for Antarctic telescope. The power supply system have the following features. First, we give priority to achieve high reliability. The reliability of power system was calculated and the redundant system is designed to make sure that the spare one can be work immediately when some parts have problems. Second, the perfect monitor system was designed to monitor the voltage, current, power and power factor for each power channel. The status of power supply system can be acquired by internet continuously. All the status will be logged in main computer for future analysis. Third, the PFC (Power Factor Correction) technology was used in power supply system. This technology can dramatically increase the power factor, especially in high power situation. The DC-DC inverter instead of AC-DC inverter was used for different voltage level to increase the efficient of power supply.

9906-222, Session PS15

The Telescopio San Pedro Martir project

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The Telescopio San Pedro Mártir (TSPM) project intends to construct a 6.5m telescope to be installed at the Observatorio Astronómico Nacional in the Sierra San Pedro Mártir in northern Baja California, Mexico. The project is an association of Mexican institutions, lead by the Instituto Nacional de Astrofísica, Optica y Electrónica (INAOE) and UNAM's Instituto de Astronomía (IA-UNAM), in partnership with the Smithsonian Astrophysical Observatory (SAO) and the University of Arizona's Department of Astronomy and Steward Observatory (UA). The project is currently in the design stage, with the goal of holding its preliminary design review in mid-2016.

The telescope will be a Magellan-like mechanical design, whose principal change is to move the Nasmyth focal stations slightly higher from the primary to allow a wider field of view. The primary mirror cell will be completely compatible with the MMT telescope's Cassegrain focus. This design is being lead by the Centro de Ingeniería y Desarrollo Industrial (CIDESI) in Querétaro, Mexico. Initially, the telescope is to operate in a f/5 Cassegrain configuration, before future definition and expansion to its other focal stations, including Nasmyth and folded Casssegrain configurations.

The enclosure is being designed by M3 Engineering and Technology Corp., through their branch in Hermosillo, Mexico. The design borrows elements from the Magellan telescopes (Las Campanas, Chile), but incorporating the particular needs of the San Pedro Mártir site. The primary mirror will be polished at the Steward Observatory Mirror Lab (Richard F. Caris Mirror Lab). The telescope will initially use the f/5 Cassegrain secondary currently at the Magellan II Clay telescope. The first light instruments are likely to be the Megacam and MMIRS instruments, currently at the Magellan II and MMT telescopes, respectively.

Once completed, we anticipate that the collaboration and coordination of the two observatories will provide their communities the benefits of a binational astrophysical observatory serving astronomers from all partner institutions, with each site focussing upon its strengths. The TSPM, thanks to its wide field imaging capability, will allow state-of-the-art research on planetary, Galactic and extragalactic astronomy, variable sky studies, and large scale surveys. TSPM will be complementary not only to the MMT for large scale, high-impact programs, but also to multi-frequency collaborations that could exploit current Mexican facilities, such as the Gran Telescopio Milimétrico Alfonso Serrano (GTM) and the High-Altitude Water Cherenkov Gamma-Ray Observatory, HAWC. The TSPM will also represent a excellent follow-up complement for +20m class telescopes after 2020.

9906-223, Session PS15

The ASTRI prototype and mini-array: telescopes precursors for the Cherenkov Telescope Array (CTA)

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In the framework of the Cherenkov Telescope Array (CTA) Observatory, the Italian National Institute of Astrophysics (INAF) has recently inaugurated in Sicily (Italy), at the Serra La Nave astronomical site on the slopes of Mount Etna, a large field of view (9.6 degrees) dual-mirror prototype (ASTRI SST-2M) of the CTA small size class of telescopes. CTA plans to install about 70 small size telescopes in the southern site to allow the study of the gamma rays from a few TeV up to hundreds of TeV. The ASTRI SST-2M telescope prototype has been developed following an end- to-end approach, since it includes the entire system of structure, mirror's optics (primary and secondary mirrors), camera, and control/acquisition software. A remarkable improvement in terms of performance could come from the operation of the ASTRI mini-array, led by INAF in synergy with the Universidade de Sao Paulo (Brazil) and the North-West University (South Africa). The ASTRI mini-array will be composed of nine ASTRI SST-2M units and it is proposed as a precursor and initial seed of CTA to be installed at the final CTA southern site. Apart from the assessment of a number of technological aspects related to CTA, the ASTRI mini-array will extend and improve the sensitivity, similar to the H.E.S.S. one in the 1-10 TeV energy range, up to about 100 TeV.

9906-224, Session PS16

ALMA long baseline phase calibration using phase referencing

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The Atacama Large Millimeter/submillimeter Array (ALMA) is the world's largest millimeter/submillimeter telescope and provides unprecedented sensitivities and spatial resolutions. The highest spatial resolution is achieved with the longest antenna spacings (baselines). Because the most extended array configuration of ALMA has up to 15 km baselines, the highest spatial resolutions are 60, 25, and 17 milli arcseconds at the receiving wavelengths of 3, 1, and 0.3 mm, respectively. With these resolutions, ALMA is expected to reveal unseen astrophysical phenomena in a variety of celestial objects. To achieve the highest imaging capabilities, interferometric phase calibration for the long baselines is one of the most important subjects: The longer the baselines, the worse the phase stability becomes because of turbulent motions of the Earth's atmosphere, especially, the water vapor in the troposphere. To overcome this subject, ALMA adopts a phase calibration scheme using a water vapor radiometer (WVR) to estimate the amount of water vapor content along the antenna line of sight. An additional technique is phase referencing, in which a science target and a nearby calibrator are observed by turn by quickly changing the antenna pointing. The WVR phase calibration is useful to mitigate phase fluctuations due to the water vapor while the phase referencing can largely remove phase noises which are commonly seen both in the interferometer phases of a target and nearby calibrator. We conducted feasibility studies of the combination technique with the WVR phase correction and phase referencing for the ALMA 15 km longest baselines in cases that (1) the same observing wavelength both for a target and calibrator is used, and (2) shorter and longer wavelengths for a target and calibrator, respectively, with a typical switching cycle time of 20 to 25 s. The latter technique is called band-to-band and fast switching (B2B+FS). It was found that the phase calibration performance of the combined technique is promising where a nearby calibrator is located within 3 degrees from a science target. The currently trial phase calibration method shows the same performance independent of the observing wavelengths. This result is especially important for the shorter wavelength observations because it becomes difficult to find a bright calibrator close to an arbitrary sky position, so that the B2B+FS can be a very useful metho especially for shorter wavelengths. In the series of our experiments, it is also found that, for ALMA, phase errors affecting the image quality come from not only the water vapor content but also a large structure of the atmosphere with a typical cell scale of a few tens of kilometers.

9906-225, Session PS16

The design of the local monitor and control system of SKA dishes

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The Square Kilometer Array (SKA) project aims at building the world's largest radio observatory to observe the sky with unprecedented sensitivity and collecting area.In the first phase of the project (SKA1), an array of dishes, SKA1-MID, will be build in South Africa. It will consist of 133 15m-dishes, which will include the MeerKAT array, for the 0.350-20 GHz frequency band observations.

Each antenna will be provided with a local monitor and control system (LMC), enabling operations both to the Telescope Manager remote system, as the to engineers and maintenance staff; it provides different environment for the telescope control (positioning, pointing, observational bands), metadata collection for monitoring and database storaging, operational modes and functional states management for all the telescope capabilities.

In this paper we present the LMC software architecture designed for the detailed design phase (DD),where we describe functional and physical interfaces with monitored and controlled sub-elements, and highlight the data flow between each LMC modules and its sub-element controllers from one side, and Telescope Manager to other side.

We also describe the complete Product Breakdown Structure (PBS) created in order to optimize resources allocation in terms of calculus and memory, able to perform required task for each element according the proper requirements. Among them, time response and system reliability are the most important, considering the complexity of SKA dish network and its isolated placement.

Performances obtained by software implementation using TANGO framework will be discussed, matching them with technical requirements derived by SKA science drivers.

9906-226, Session PS16

Design and analysis of a large cylinder antenna array in Tianlai

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In order to make a large area survey, precisely measure a large scale space and detect dark energy, a large radio interference array with a large number of feeds is required. However, the cost and the deformation measurement are very important in designing a large antenna array. This paper presents a structure design of one cylinder parabolic antenna array with 45m x 40m, which was built for "Tianlai" project in Xinjiang, China in 2015. In order to largely reduce the weight and the cost, we divided it into many assemble units which were optimized in mechanical design by MSC.Patran/Nastran, then analyzed the deformation of the reflector under various load cases of gravity, snow and wind. For the feed support structure, we designed and compared some supporting types such as arch bridge, tower, cable and pole. Mechanical and electromagnetic field simulations show that the arch bridge is very useful to complete the large span, and the antenna structure is very light and stable. Finally some measurement methods and experiments for the deformation are discussed. These results will be used to extend this array to 100m x 100m in the future.

9906-227, Session PS16

Measuring dark energy and radio transients with HIRAX

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The Hydrogen Intensity and Real-time Analysis eXperiment (HIRAX) is a new 400-800MHz radio interferometer under development for deployment in the Karoo Desert, South Africa. It will have 1024 5-m parabolic dishes on a compact grid, and will map the entire Southern sky over the course of 2 years. HIRAX has two primary science goals: to constrain Dark Energy and measure structure at high redshift and to study radio transients and pulsars.

HIRAX will measure unresolved sources of neutral hydrogen via their redshifted 21cm emission line (hydrogen intensity mapping). The resulting maps of large scale structure at redshifts 0.8--2.5 can be used to measure Baryon Acoustic Oscillations (BAO). BAO are a preferential scale in the matter distribution created with the Cosmic Microwave Background which we can use to chart the expansion history of the Universe and thus understand the nature of Dark Energy. BAO measurements with HIRAX will improve current error bars from galaxy surveys by observing a larger cosmological volume (both from increased survey area and redshift range), and will also measure BAO at high redshift when the expansion of the Universe transitioned to Dark Energy-dominated. HIRAX will complement CHIME, a hydrogen intensity mapping effort in the Northern Hemisphere, by completing the sky coverage in the same redshift range. HIRAX's location in the Southern Hemisphere also allows a variety of correlation measurements with surveys of structure at many wavelengths.

Daily maps of 15,000 square degrees of the southern hemisphere will also be a new approach for discovering and monitoring radio transients. With access to the entire plane of the Milky way galaxy, HIRAX is building into its correlator the ability to rapidly and efficiently detect transients. The results will shed light on the poorly understood nature of Fast Radio Bursts (FRBs), have a critical monitoring role in pulsar timing arrays to detect long-wavelength gravitational waves, and find new radio transient phenomena.

In this paper, I will discuss the HIRAX instrument, science goals, and current status.

9906-228, Session PS16

Super-resolution with Toraldo pupils: analysis with electromagnetic numerical simulations

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The concept of superresolution refers to various methods for improving the angular resolution of an optical imaging system beyond the classical diffraction limit. In optical microscopy, several techniques have been developed with the aim of narrowing the central lobe of the illumination Point Spread Function (PSF). In Astronomy a few methods have been proposed to achieve reflector telescopes and antennas with resolution significantly better than the diffraction limit, from the use of "metamaterials" (May & Jennetti, 2004) to exploiting the "quantum cloning" effect (Kellerer, 2014). However, no working system is in operation, yet. A more practical approach consists of using the so-called "Toraldo Pupils" (TPs) or variable transmittance filters. These pupils were introduced by G. Toraldo di Francia in 1952, and consist of a series of concentric circular coronae providing specific optical transparency and dephasing in order to engineer the required PSF. The first successful laboratory test of TPs in the microwaves was achieved by Mugnai et al. (2003), and in the present work we build upon these initial measurements to perform electro-magnetic (EM) numerical simulations of TPs, using a commercial full-wave software tool. These simulations were used to study various EM effects that can mask and/or affect the performance of the pupils and to analyze the near-field as well as the far-field response.

Our EM analysis confirms that at 20 GHz the width of the central lobe in the far-field generated by a TP significantly decreases compared to a clear circular aperture with the same diameter. We also used these EM simulations to prepare more comprehensive laboratory testing, with the final goal to study a prototype TP to be mounted on a radio antenna. Some preliminary experimental results confirming the EM simulations and the early measurements by Mugnai et al. (2003) will be discussed.

9906-229, Session PS16

Simulating photogrammetric measurements of the Sardinia Radio Telescope

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The Sardinia Radio Telescope (SRT) is a fully steerable 64-metre diameter quasi-parabolic radio telescope located in Sardinia (Italy), equipped with active surface system to recover deformations due to gravity, wind and temperature gradients. Its primary mirror is composed by 1008 panels supported by electromechanical actuators, digitally controlled, together with a 6-degrees of freedom mechanical movement of the subreflector.

To observe at its highest operating frequency, SRT needs an antenna pointing angular precision of about 1 arcsec and a primary mirror surface accuracy better than 300 microns RMS. Furthermore, the performances improvement of the active systems needs an independent measuring system to control movements and deformations during the telescope operations.

Photogrammetry is a non-contact measuring technique which can accurately measure the shape and the orientation by means of photographs. Concerning SRT, It showed the capability to achieve the required performances. In fact, it has been used during the first alignment of the SRT optics, as well for the surface accuracy improvement of several other radio telescope. However this technique can not be used during the operations of a radio telescope, because their large structures requires cranes and operators to take the needed photographs.

We developed a photogrammetric measurements simulator: starting from accurate 3D model of the SRT, the simulator can generate of synthetic photo realistic images as a function of the number and geometry of survey, and of the camera parameters like focal length and resolution.

Hence, we simulated several survey geometries, selecting those that allowed the best measurement accuracy. Moreover the complete 3d model allows us to perform photogrammetric simulations over the whole structure.

The simulator, in fact, is aimed to general purpose, open to each scenario having an accurate 3d model, optimising the needed resources for a photogrammetric survey.

9906-230, Session PS16

AM-AM/AM-PM distortion versus complex Volterra kernels for modeling RF transceiver blocks

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Power amplifiers and other RF blocks are often modeled using the AM-AM / AM-PM distortion model. This model turns the input complex envelope (the signal before distortion) into an output complex envelop (the signal after distortion) where both the gain and the phase shift depend nonlinearly on the input power (the norm of the complex envelope).

Working in the complex domain of the complex envelop, simulations can be carried out at a sample rate as low as the RF/IF bandwidth of the signal, while a model working in the RF domain would need to work at more than twice the maximum RF frequency, because the bandwidth of the complex envelop is half that of the real signal. This reduces the cost of system modeling and simulation.

The traditional AM-AM/AM-PM model can be accurate for narrowband signals, but it is increasingly less accurate as the bandwidth of the signal increases. In this paper, it is shown that the standard AM-AM/AM-PM model can be considered a Volterra kernel without lags, and that adding lags to the Volterra kernel improves the accuracy of the model.

The traditional model and the proposed complex Volterra model are used to model distortions in a real receiver mixer (RF-to-IF downconversion), in a real transmit mixer (IF-to-RF upconversion), in an IF receiver amplifier, and in an RF power amplifier.

Digital complexity versus accuracy is the main trade-off where models are compared, as accurate models tend to have a larger number of parameters and require more operations to simulate the system in real time. Iterative pruning techniques are used to minimize the complexity of Volterra kernels given a certain level of accuracy.

These models can be used for the calibration of RX and TX systems, as digital calibration consists in cascading the inverse digital model to the original analog system to obtain a combined model with higher linearity.

Calibration can be logically separated in three steps. The first is modeling, when a parametric model of the system (ideally both simple and accurate) is obtained. Then estimation, when the parameters are estimated to obtain the best fit (either offline or online). Finally correction, when the output of the inverse model is computed and applied to the distorted output of the analog system to obtain a linearized cascaded system.

In order to compute the inverse model, an accurate model of the system shall be obtained, and the parameters shall be estimated, either online or offline. In the case of online (background) calibration, the number of free parameters in the model also increases the computational cost of the estimation step. The correction step is instead always performed in real-time and its cost is the same in offline and online calibration.

9906-231, Session PS16

An innovative, highly sensitive receiver system for the Square Kilometre Array Mid Radio Telescope

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The Square Kilometre Array (SKA) project is a global science and engineering project aiming at designing and constructing the next-generation radio telescope operating in the metre and centimetre wavelengths regions. The first phase of construction of the telescope (SKA1), which represents roughly 10% of the full SKA (SKA2), is currently well advanced with its design and expected to be operational early next decade. The SKA radio telescopes will be co-hosted in two locations with central array sites in Australia, SKA1-Low (50 – 350 MHz), and South Africa, SKA1-Mid (350 MHz – 13.8 GHz with an option for > 20 GHz).

This paper addresses design concepts of the broadband, exceptionally sensitive receivers and reflector antennas deployed in the SKA1-Mid radio telescope.

SKA1-Mid will consist of 133 reflector antennas using an off-set Cassegrain configuration with an effective diameter of 15 m. The unblocked aperture results in increased aperture efficiency and lower side-lobe levels compared to a traditional on-axis configuration. The low side-lobe level reduces the noise contribution due to ground pick-up but also makes the antenna less susceptible to ground-based RFI sources. The addition of extra shielding on both main and sub-reflectors provides a further reduction of ground pick-up. The optical design of the SKA1_mid reflector antenna has been tweaked using advanced EM simulation tools in combination with sophisticated models for sky, atmospheric and ground noise contributions.

Initially SKA1_Mid will be equipped with three receiver bands, Band 1 (350 – 1050 MHz), Band 2 (950 – 1760 MHz), and Band 5 (4.6 – 13.8 GHz). Despite the relatively large RF frequency band, up to a ratio of 1:3, the sensitivity is very competitive compared with other radio telescopes.

For Band 1 both cooled and uncooled concepts have been investigated. The advent of new semiconductor devices in this frequency range enables a design solution which has comparable sensitivity to the traditional alternative using cryogenically cooled low noise amplifiers. A quad-ridged feed horn will be used to illuminate the reflector antenna. This feed design provides the required wideband performance while still having relatively compact dimensions. Nevertheless, due to the feed dimensions, the feed itself cannot be cooled. The absence of any cryogenic cooling for this band will be a major advantage in the operations phase of the radio telescope because of reduced power and maintenance costs.

The Band 2 receiver makes extensive use of cryogenic cooling for the low noise amplifiers and part of the feed system. This approach has resulted in a sensitivity which is probably best in class for cm radio telescopes.

The Band 5 receiver is a recent addition to the SKA1-Mid telescope based on revisited science priorities. Like Band 2 it will make extensive use of cryogenic cooling.

Another novel concept for radio telescopes is that in SKA1-Mid no frequency conversion in the analogue front end is foreseen. Instead all RF signals are directly digitized after amplification. Except for broadband, anti-aliasing, filtering in the RF chain all bandpass filtering and frequency conversion will be performed in the digital domain. This direct digitization concept avoids the need for local oscillator signals, introducing the risk of unwanted spurs, and gives increased flexibility in catering the different back-ends dedicated to different types of astronomical science.

9906-249, Session PS16

Preliminary running and performance test of huge cable robot of FAST telescope

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The highly flexible huge cable-driven parallel robot is one of the innovations of FAST that makes FAST different from many other radio telescopes. It connects dynamically the airborne feed with the main reflector, and controls preliminarily the feed pose in process of following transient focus point of the telescope in the observation mode. Although feasibility of the design has been preliminarily proved via Sino-Germany end-to-end simulation in 2007 and demonstrations of a few downscale models, a lot of details are expected to be testified on prototype especially after the detailed design had been finished in 2013.

In the middle of 2015 the construction of the prototype was nearly complete. On November 15 the movable platform, namely the focus cabin, was successfully pulled airborne by six parallel steel cables from the cabin harbor on the bottom of the depression. Although the cabin brings nothing but the outer main structure and necessary sensors, both its size and weight as well as mass distribution are quite similar to the real one. It gracefully drifted in the air along designated trajectory with small vibration under gentle breeze.

During the following two months, a set of performance tests were done to verify a few key design parameters. First, 6 actual cable tensions were measured throughout all important cabin positions on the focal surface. The comparisons between the data and analytical values show good consistency except that maximal force error of 3 tons exists on the edge of the focal surface. Second, some dynamic parameters like natural frequency and damping ratio are tested via vibration analysis for the flexible cabin-cable suspension system. The natural frequencies are quite near to the values given by the end-to-end simulations, but the damping ratio is obviously a little higher than that in the simulation on several typical cabin positions.

Higher damping assures better energy dissipation and in turn increases the controllability of positioning the feed via flexible cable robot. Finally the positioning/pointing accuracy is analyzed via running the cable robot to follow a set of carefully prepared trajectories. The tests help evaluate the control algorithms and parameters and then finalize them. The results prove that the cable robot is capable of driving the feed to desired pose with translational error less than 48mm and orientation error less than 1 angular degree, meeting the requirement given in the end-to-end simulation.

9906-232, Session PS17

FACT: the self-calibrating camera of the first G-APD Cherenkov telescope

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The First G-APD Cherenkov Telescope (FACT) is pioneering the usage of solid state photosensors (G-APD aka SiPM) for Imaging Atmospheric Cherenkov Telescopes (IACT) that measure the very short and dim flashes of Cherenkov light induced by high energetic particles entering the atmosphere.

The strong temperature dependence of the SiPM gain poses a challenge for IACTs. Applying corrections during the analysis stage is not sufficient, since the gain changes by about 4% per K while environmental temperature variations can reach 30 K. To avoid hampering the trigger, it is necessary to ensure stable gain during operation. Instead of a complicated system for temperature stabilization of the SiPM, we have chosen to adjust the applied bias voltage according to the temperature. Initial intention was to use a temperature independent external light pulser to regularly illuminate the camera, as is usually done for IACTs, analyze the signals in real time and apply the calculated corrections to the power supplies. For cross-checks, about 30 temperature sensors were installed in the sensor compartment. These temperature sensors are not directly measuring the temperature of the individual SiPM and their distribution was not optimized. Nevertheless, during early operation it became soon evident that this temperature information is sufficient to adjust the bias voltages at least as precise as can be done with the light-pulser. Therefore, FACT is now fully relaying on the measured temperatures and there is no need for any external light-pulser, simplifying operation and maintenance.

In addition, analyzing the dark-noise and crosstalk signals intrinsic to SiPM allows to directly extract the gain of each sensor with high precision. This delivers the necessary information to homogenize the gain among all 1440 sensors of the FACT camera. The measured gain-difference over the full FACT camera is less than 2.1%, dominated by the resolution of the power supplies used.

Last but not least, the amount of measured Cherenkov flashes induced by the constant flux of charged cosmic ray particles as well as the analysis of ring-like images due to atmospheric muons deliver additional information about timing and stability of each individual sensor as well as about performance of the complete system.

In this presentation we will describe the methods used in FACT to reach a very stable SiPM camera and the experience gained. We will show the excellent stability reached during more than four years of operation of FACT so far. In addition, we will propose improvements to the methods for future systems.

9906-233, Session PS17

The DAG project, a 4m-class telescope: the telescope main structure performances

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Dogu Anatolu Gözlemevi (DAG-Eastern Anatolia Observatory) Project is a 4m class optical, near-infrared Telescope and suitable enclosure which will be located at an altitude of ~3.170m in Erzurum, Turkey.

The DAG telescope is a project fully funded by Turkish Ministry of Development and the Atatürk University of Astrophysics Research Telescope - ATASAM.

The Project is being developed by the Belgian company AMOS (project leader), which is also the optics supplier and EIE GROUP, the Telescope Main Structure supplier and responsible for the final site integration.

The design of the Telescope Main Structure fits in the TBO Program which aims at developing at a Dome/Telescope systemic optimization process for both performances and competitive costs based on previous project commitments like NTT, VLT, VST and ASTRI.

The optical Configuration of the DAG Telescope is a Ritchey-Chretien with two Nasmyth foci and a 4m primary thin mirror controlled in shape and position by an Active Optic System.

The main characteristics of the Telescope Main Structure are: an Altitude-Azimuth light and rigid structure system with Direct Drive Systems for both axis, AZ Hydrostatic Bearing System and Altitude standard bearing System; both axes are equipped with Tape Encoder System.

An innovative Control System characterizes the telescope performances.

9906-234, Session PS17

A control system of a mini survey facility for photometric monitoring

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We have built a control system of a mini survey facility dedicated for photometric monitoring of nearby bright (K<5) stars in the near-infrared. The facility is composed of a rotating dome with 4-m diameter, a small sized (30 mm aperture) wide-field (2 x 2 sq.deg. F.O.V.) infrared (1.0-2.5 micron) camera equipped on a fork-equatorial mount, power sources, etc. All of these components, except for the camera, are controlled by a micro-computer based I/O board which has developed in-house and used in many open-use instrument of our observatory. In this paper, we will present the specifications and configuration of the facility hardware as well as the structure of the control software.

The near-infrared camera is dedicated for photometry of bright nearby stars. The camera consists of single calcium-fluoride lens(30 mm in diameter) and a 2K x 2K HgCdTe array detector, yields 2 x 2 square degrees field of view and enables precise measurement of bright (K<5) stars. Recent rapid progress of near-infrared array detectors and telescope technology have broadened the infrared universe toward dark-end. However the infrared bright-end universe has left almost un-explored since the Two Micron Sky Survey (1969). Therefore we have started a new project to monitor all the bright stars in the near-infrared visible from Okayama Astrophysical Observatory, Japan.

It is required to make the observation fully robotic. The control system is designed to be simple.

The hardware of the control system consists of a host computer, a terminal server, I/O boards, terminals and peripheral devices. All the peripherals, except for the camera, are locally controlled by a micro-computer (H8S/2633R) based I/O board which has developed in-house and has been improved over a decade. The board has 50 bit inputs, 18 bit outputs for the peripherals, and two RS232C interfaces to communicate with the host computer. The board can be widely applied to most of devices. One can freely set up the I/O ports by writing own built-in code to match control targets.

The host computer is installed software of the own making coded in Java. The software consist of three parts, calculating the position of stars, logging status and communication with several devices, such as I/O boards, external weather sensor and observation instrument. Status obtained from devices is displayed on graphical user interface.

In addition, as safety measure, the system shuts down immediately and automatically in an emergency, such as suddenly raining or when the equatorial attitude approaches horizontally. The emergency system doesn't depend on I/O boards and software, so if I/O boards or the host PC malfunctions, the emergency system would function.

9906-235, Session PS18

MeerLICHT and BlackGEM: custom-built telescopes to detect faint optical transients

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A consortium led by the Radboud University (Nijmegen, NL) is currently developing wide-field optical telescopes to study transient phenomena, gravitational wave counterparts and variable stars. The telescopes have 65cm primary mirrors and are equipped with an STA1600 detector which provides a 2.7 square degree field of view at 0.56 arcsec /pixel. A prototype telescope, called MeerLICHT, is currently being built and will be commissioned at Sutherland (South-Africa) at the end of 2016. MeerLICHT will co-point with the MeerKAT radio array, to collect optical data commensurate with the radio observations. This novel combination of a radio telescope and a dedicated co-pointing optical telescope will, amongst other things, allow us to obtain unique data on fast radio transients, by eliminating the time consuming step of triggering optical follow-up after a radio event is detected.

In parallel with the first MeerLICHT observations, three identical telescopes will be commissioned in La Silla (Chile), currently planned for the end of 2017. These telescopes form the first phase of the BlackGEM array, which aims at detecting and characterizing optical counter parts of gravitational wave events detected by the Advanced LIGO and Virgo interferometers.

The telescopes have been designed to operate robotically with limited maintenance and human intervention. The modified Dall-Kirkham optical design and the carbon-fibre mechanical design are optimized to take full advantage of the excellent observing conditions at La Silla to rapidly find faint transient sources in large areas of the sky. Advanced systems have been designed to maximize the performance, including an actively controlled secondary mirror and a novel Atmospheric Dispersion Corrector (ADC) which works by displacing one of the corrector lenses so that extra optical elements can be avoided. A limiting magnitude of 23 can be reached in less than five minutes in a wide optical bandpass.

In this contribution, we will present the design and main science goals of the telescopes.

9906-236, Session PS18

The first year of operation of MASCARA: on-sky results and the upcoming southern station

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MASCARA, the Multi-site All-Sky CAmeRA, is a project aimed at finding exoplanets transiting the brightest stars, in the V = 4 to 8 magnitude range, currently probed neither by space- nor by ground-based surveys. The target population for MASCARA consists mostly of hot Jupiters, for which the average transit depth is around 1%, and hot Neptunes. In order to achieve consistently a signal-to-noise-ratio of better than 100 per hour at magnitude 8, MASCARA is based on three main concepts; simplicity stability and calibration.

MASCARA was designed with a minimum number of moving components. Five fixed, shutter-less, Peltier-cooled cameras, fitted with standard Canon 24 mm f/1.4 lenses are operating in a temperature controlled environment. Each camera constantly stares at the same patch of the sky. The exposure time is set to 6.4 seconds, keeping trailing of stars and saturation to a minimum while allowing for continuous exposures. Each camera is connected to its own control- and data processing computer, allowing for fully independent operation of each of the cameras. Each camera takes between 4,000 and 7,000 exposures per night, which are reduced locally to produce un-calibrated light curves for the up to ~40,000 pre-selected stars, as well as image stacks of 50 images. For each set of 50 images, astrometry of the solution is verified to monitor drifts in the station. Currently both reduced data as well as raw data (~500 GB/night) are transferred to a central data repository, but for stations with less bandwidth, potentially only the reduced data could be transferred. MASCARA currently only permanently stores the reduced light curves and binned image stacks, deleting the raw images after one month.

After transfer, the raw light curves are self-calibrated in batches of 2-4 weeks, removing the spatially-varying transmission of the camera, the impact of crowding and spatially-variable PSF, and the time-variable transmission of the atmosphere. Using a combination of SysRem and flagging of data points that are impacted by known artifacts (moon, sun, clouds, etc), we have demonstrated a photometric stability of MASCARA down to 0.3% at magnitude V=7.7 within 5.3 minutes.

In this paper we present the results obtained with the first MASCARA station, lessons learned and a preview to our second station, to become operational in mid-2016.

9906-238, Session PS18

First results of the Test-Bed Telescopes (TBT) project: Cebreros telescope commissioning

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The TBT project is being developed under ESAs General Studies and Technology Programme, and shall implement a test-bed for the validation of an autonomous optical observing system in a realistic scenario within the Space Situational Awareness (SSA) programme of ESA.

The system consists of two telescopes, one in Spain and the second one in the Southern Hemisphere. The telescope is a fast astrograph with a large FoV of 2.5º x 2.5º and a plate scale of 2.2 arsec/pixel. The tube is mounted on a fast direct-drive mount moving with speeds up to 20º/sec. The focal plane hosts a 2-port 4k x 4k 15-micron pixels back-illuminated CCD with read-out speeds up to 1MHz per port. All these characteristics ensure good survey performance for transients and fast moving objects.

Detection software and hardware are optimised for the detection of NEOs and objects in high Earth orbits (objects moving from 0.1-40 arsec/second). Nominal exposures are in the range from 2 to 30 seconds, depending on the observational strategy. Part of the validation scenario involves the scheduling concept integrated in the robotic operations for both sensors. Every night it takes all the input needed and prepares a schedule following predefined rules allocating tasks for the telescopes. Telescopes are managed by RTS-2 control software, that performs the real-time scheduling of the observation and administers all the devices at the observatory. Appart from all the weather sensors, the safety system has redundant sensors to monitor weathear and other possible hazards for the observatory. At the end of the night the observing systems report astrometric positions of the objects detected.

The first telescope was installed in Cebreros Satellite Tracking Station in mid 2015. It is currently in the commissioning phase and we present here the first results of the telescope. We evaluate the site characteristics and the performance of the TBT Cebreros telescope in the different modes and strategies. We present the final figures of the telescope parameters and the first results of NEOs surveys and follow-ups. Telescope has good pointing capabilities (10 pixels rms) and overall astrometric precision is 0.4" rms. Objects down to magnitude 20 are regularly observed in moonless nights. The telescope is a valid prototype and the Southern Hemisphere counterpart, with astronomical-quality skies, is going to be a very competitive survey instrument. The second telescope is foreseen to be installed and commissioned by Autumn 2016.

9906-239, Session PS18

Final design of the LSST secondary mirror assembly

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The Large Synoptic Survey Telescope (LSST) has a 10 degrees square field of view which is achieved through a 3 mirror optical system comprised of an 8.4 meter primary, 3.5 meter secondary (M2) and a 5 meter tertiary mirror. The M2 is a 100mm thick meniscus convex asphere. The mirror surface is actively controlled by 72 axial electromechanical actuators (axial actuators). Transverse support is provided by 6 active tangential electromechanical actuators (tangent links). The final design has been completed by Harris Corporation. They are also providing the fabrication, integration and testing of the mirror cell assembly, as well as the figuring of the mirror. The final optical surface will be produced by ion figuring. All the actuators will experience 1 years of simulated life testing to ensure that they can withstand the rigorous demands produced by the LSST survey mission. Harris Corporation is providing optical surface metrology to demonstrate both the quality of the optical surface and the correctablility produced by the axial actuators. As a result of the difficulties involved in providing surface metrology for a large convex optic, it is not practical to produce a single image of the optical surface. Consequently, multiple images will be stitched together during metrology to evaluate the optical surface.

9906-241, Session PS18

Wavefront-based PSF estimation

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A new method to estimate the Point Spread Function from measurements of optical wavefront is described. Out-of-focus (engineering) Dark Energy Camera (DECam) images are analyzed, using the donut algorithm from the DECam Active Optics System, to characterize the Blanco + DECam optical wavefront with a pupil Zernike decomposition. Our PSF model consists of the measured wavefront combined with physically motivated adjustments with up to three parameters per Zernike term. Next, the adjustable parameters of the PSF model are fit to stars are selected from Dark Energy Survey (DES) Science Verification (SV) images, using just adaptive second moments of the stars and the PSF model. Results from SV r, i and z band images are presented. To account for remaining differences between stars the the PSF model, we use the Richardson-Lucy deconvolution algorithm to estimate the difference kernel. Lastly, we interpolate across each CCD to characterize the difference between data and the wavefront PSF model. We perform a detailed comparison of the Wavefront-based PSF estimator against the DES PSF model.

9906-242, Session PS19

Fast tip-tilt segment alignment for segmented mirrors

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Optical alignment of segments is one the recurring tasks when using segmented mirrors, for example in telescopes. Although edge sensors maintain mirror shape for a long time, new alignment is needed regularly after the segments are changed and the calibration might be lost. The alignment is particularly demanding when the segments are misaligned in tip and tilt to such extent that each of the segments forms a separate image on the focal plane, possibly scattered over an area of several arc-minutes and identification of the segments is difficult. A method to treat this problem has been developed at the Isaac Newton Group of Telescopes. First it was used for alignment and calibration of the 76-segment deformable mirror for NAOMI adaptive optics system at the 4.2-metre William Herschel Telescope (WHT). Later it was adapted for alignment of the 36-segment primary mirror of the 10.4-metre Gran Telescopio Canarias (GTC). In the latter case the time necessary for alignment is on average about 10 minutes after the guide star is acquired. Most of the time is spent waiting for the segments to stabilise after they are moved and waiting for the acquired image to appear in the file system.

A dedicated application was written in Python to support this task. It allows visual representation of segments and triggering of different actions from the GUI such as identification of selected segments, fine alignment after the identification and spiral search for badly misaligned segments.

The method relies on known and well-calibrated relations between the change of tip and tilt of individual segments and the amount of image motion in the focal plane. Using these relations, it is possible to identify images of the alignment star made by different segments. By moving each segment by a different amount and in a different direction it is possible to apply the method to many segments at once. The segments are identified by a pattern-matching algorithm which finds spots that have moved by a segment-specific predicted vector from one image to another. To minimise chances of confusion, several images are used, usually 5. In the case of the GTC mirror, this method allows for the simultaneous alignment of all segments.

The method does not need any special optical setup; only an imaging camera with a field of view of a few arc-minutes is required. This will typically be an existing imaging or acquisition camera.

The applicability of the method for alignment of the primary mirrors of the giant future telescopes such as the E-ELT and the TMT is discussed. Due to the large number of segments this is more complicated than for the GTC because a larger number of background stars appears in the field of view. Simulated images based on real star catalogues are used for increased realism of the simulation. Different strategies are examined and the results presented for aligning a completely misaligned mirror, as well as for cases when only a subset of segments needs alignment.

9906-243, Session PS19

The alignment and phasing system for the Thirty Meter Telescope: risk mitigation and status

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The Alignment and Phasing System (APS) is responsible for the optical alignment via starlight of the approximately 10,000 degrees of freedom in the primary, secondary and tertiary mirrors of the Thirty Meter Telescope (TMT). APS is based on the successful Phasing Camera System (PCS) used to align the Keck Telescopes. Since the successful APS conceptual design in 2007, work has concentrated on risk mitigation, use case generation, and alignment algorithm development and improvement. Much of the risk mitigation effort has centered around development and testing of prototype APS software which will replace the current PCS software used at Keck. We present an updated APS design, example use cases and discuss, in detail, the risk mitigation efforts.

9906-244, Session PS19

Self-coherent camera as a focal plane phasing sensor

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Forthcoming generation of space- and ground-based observatories will deliver considerably large angular resolution. So as to reach this unprecedented angular resolution, and because the primary mirror of these telescopes will be segmented, each segment will require to be positioned with high accuracy.

With the increased dimension and complexity of telescopes (missing segments, island effect, pupil shear, etc.), co-phasing technics and in particular pupil plane approaches will be severely affected. To overcome these effects, we propose to adapt the Self-Coherent Camera as a focal plane phasing sensor in order to provide a powerful and straightforward solution directly analyzing the signal from the segment surface.

After presenting the principle of the sensor, we present results obtained by means of intensive numerical simulations.

We explore the parameter space of this new sensor through an in-depth analysis of the system calibration, closed-loop performance, sky coverage, and sensitivity to misalignments.

Finally, laboratory testing of this new co-phasing sensor on the Segmented Pupil Experiment for Exoplanet Detection (SPEED) will be detailed. The SPEED bench makes use of a 169-segments mirror from IrisAO vendor controllable in piston, tip and tilt that will be operated in a switchable optical configuration providing ambivalent analysis in both pupil and focal plane for comparison purpose with other co-phasing techniques.

9906-245, Session PS19

Calibration and operation of the active surface of the Large Millimeter Telescope

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The Large Millimeter Telescope relies on an active primary surface to achieve its specified surface accuracy. The active primary has two functions: (1) it provides a means to correct the surface for gravitational deformations with changing elevation; and (2) it provides a capability to improve the shape of the surface in real time due to transient effects of thermal gradients within the structure. At LMT, our development work has addressed both problems and in this paper we describe the derivation of the gravity deformation model and the schemes developed to measure and improve the antenna surface during regular scientific observations. The LMT's active surface consists of 180 trapezoidal surface segments arranged in 5 annular rings. Each segment is attached to the antenna backup structure with an actuator at its four corners, which allows segments to be repositioned in order to maintain a precise parabolic surface. Once the active surface system is in place, the challenge is to measure the response of the antenna to stresses that tend to deform it, and to put models in place that will allow compensation.

Gravitational deformations of the structure should be straightforward since they depend only on the orientation of the structure with respect to gravity. In principle, the gravitational deformations may be measured and then compensated using an open-loop lookup table. At the LMT, our approach has been to use a radio holography technique to measure the surface using a set of geostationary satellites at different elevation angles. Maps of the surface obtained at each elevation that is sampled are then used to derive the lookup table. The holography maps excel at setting the relative positions of the segments accurately. However, experience with implementing this procedure in practice shows that systematic errors in the measurements and the limited elevation sampling of the surface mapping can lead to significant uncertainties in the extrapolation of models beyond the elevation range that is sampled. Moreover, in measurements of a real structure, the gravitational deformations must be separated from other effects of the environment which lead to changes from night-to-night and within a given night.

Deformations due to environmental effects, such as those induced by temperature gradients within the structure, must also be dealt with by the active surface system. Holography measurements during the course of the night have shown that the main feature of the LMT's thermal deformation is an astigmatism. Thus, the appearance of this particular deformation is easy to identify during routine focusing of the telescope, and it is straightforward to correct simply by adjusting the shape of the surface using Zernike astigmatism term to optimize the gain. Development of out-of-focus holography techniques is underway to provide a means to measure and correct other low-order Zernike terms.

9906-246, Session PS19

Performance of the Giant Magellan Telescope phasing system

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The 25.4m Giant Magellan Telescope consists of seven 8.4 m primary mirror (M1) segments with matching segmentation of the Gregorian secondary mirror (M2). When operating the telescope in the diffraction-limited Adaptive Optics (AO) observing modes, the M1-M2 pairs of segments must be phased to a small fraction of the observing wavelength. To achieve this level of correction, the phasing system relies on edge sensors to sense high temporal frequency disturbances (mainly due to wind buffeting against M1 and M2 segments), and uses multiple natural guidestar phasing sensors deployed across the field of view to provide an absolute phasing reference on minute timescales.

We will present in this paper the performance characterization of the GMT phasing system based on end-to-end numerical simulations performed with the Dynamic Optical Simulation (DOS) tool, which integrates the optical and mechanical dynamics models of the GMT with the Fourier optics models of AO and phasing sensors. The simulation also includes most major optical disturbances, and captures the interactions between the multiple nested wavefront control loops. The expected phasing performance under different observing conditions will be presented.

9906-247, Session PS19

Focal plane wavefront sensing for active optics in the VST based on an analytical optical aberration model

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We report on successful closed-loop active optics control of the 2.6 m VST survey telescope using focal plane wavefront sensing. The method extracts a large number of stars from the science images observed with the 256-Mpixel OmegaCAM visible-light camera and measures their PSF sizes and ellipticities. Starting from an analytical telescope aberration model based on 5th-order geometrical optics, we then solve the inverse problem of matching the observed seeing-corrected ellipticity pattern across the field to a set of mirror misalignment and disfigure degrees of freedom. We then compute the maximum likelihood telescope misalignment state using all recently recorded images and correct it in real time. This novel type of active optics control does not require additional hardware. Moreover, it validates our aberration model which we believe has a number of other potential applications.

9906-248, Session PS19

Phasing the segments of the Keck and Thirty Meter Telescopes via the narrowband phasing algorithm

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We have developed two methods of phasing the segments of the Keck telescopes: narrowband (NB) phasing, in which the length standard is the wavelength of one or more narrowband filters, and broadband (BB) phasing, in which the standard is the coherence length of a generally broader filter or filters. The NB approach incorporates the familiar technique of making measurements at multiple wavelengths in order to form a large artificial wavelength and thereby extend the capture range. NB phasing is faster and more accurate (~10 nm) than BB phasing (~30 nm), but in practice it suffers from an apparent instability in which the solution jumps to the wrong branch of the quasi-periodic response curve a few percent of the time. For this reason, we have favored the more stable BB algorithm at Keck, but the increased speed and accuracy of the NB algorithm will be needed to phase the segments of the Thirty Meter Telescope. Consequently we have undertaken a detailed study of NB phasing at Keck. We have shown that the apparent instability is in fact due to small systematic wavelength-dependent errors associated with the edge height measurements. These appear to originate at the segments themselves, and not inside of the phasing camera. Possible sources of these wavelength-dependent errors will be discussed. We will present data on their stability over time, their potential consequences, and the extent to which they can be calibrated out.

9906-75, Session 21

SKA Telescope update through re-baselining and preliminary design phase *(Invited Paper)*

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During the past year the Square Kilometre Array Project has progressed aggressive development phase. Since 2008, the global radio astronomy community has been engaged in the development of the SKA in a major effort - the ‘Preparatory’ phase of the project. The Preparatory phase ended in December 2011 and, following a number of major changes, the international SKA project has now progressed to the ‘Pre-Construction’ phase (2012-17). The Member Nations have set up the SKA Organisation, a not-for-profit company founded in the UK to lead activities and the Pre-Construction work has been organised into a series of design work packages to be delivered by consortia from the Member Nations. During the past 12 months the project has moved through a re-baselining phase to reduce the observatory to fit into funding available. In addition, the project has moved through a series of Preliminary Design Reviews. This paper describes the organisation and scope of the work packages as the project begins the work of preparing for SKA1 construction. It will cover issues of management and value engineering, as well as risk management and systems engineering. In addition, lessons learned from PDR and Re-Baselining.

9906-76, Session 21

MeerKAT: a project status report

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The MeerKAT radio telescope is currently in full production in South Africa’s Karoo region, and by association, so is the Square Kilometre Array Phase 1 (SKA1) MID telescope. MeerKAT will be the largest and most sensitive radio telescope array in the centimetre wavelength regime in the southern skies until the SKA1 MID telescope is operational, and is well on its way to realising the MeerKAT vision of being a world class instrument that exceeds its original specification. This paper identifies the key telescope specifications, discusses the high-level architecture and current progress to meet the specifications and lastly reports on lessons learnt in the process.

Sensitivity was set as a key specification for MeerKAT, with a requirement to achieve a sensitivity of 220m2/K at L-band. The measured performance of the L-band receiver currently indicates a ~40% improvement in sensitivity. With high sensitivity comes the requirement to have a matching imaging dynamic range, with signal stability over the imaging period. The offset Gregorian dish configuration provides for a clean optical path, with low sidelobe levels and good rejection of radio frequency interference. MeerKAT will consist of 64 offset Gregorian dishes at 13.5m diameter each, with manufacturing, installation and assembly of 14 dishes by year-end 2015, completing the dish roll-out in 2017. Seventy percent of the dishes will be deployed in a compact core, with an extended array providing for high fidelity imaging performance over a range of resolutions from 6 arcsec to approximately 100 arcsec.

L-band and UHF band receivers spanning 0.9-1.67GHz and 0.58-1.015GHz respectively will allow neutral hydrogen to be detected up to a redshift of z=1.45, probing back 9.2 Gyrs into the distant universe. Plans are being put in place to fit X-band (8-14.5 GHz) and S-band (1.75-3.5 GHz) frequency receivers onto each dish’s receiver indexer. MeerKAT science projects include pulsar timing, deep neutral hydrogen surveys, galaxy surveys, searching for carbon monoxide lines, fast radio bursts and other radio transients. Large survey project teams have been invited to present updated project plans during 2016 given the updated technical specifications and capabilities of MeerKAT.

All telescope subsystems are currently in production, including dishes, receivers, digitisers, correlator/beamformer, receptor fibre network, control and monitoring and science processing. Qualification, integration and acceptance testing is taking place at all levels.

Several valuable lessons have been learnt thus far. Problems downstream in the signal chain are generally symptoms of neglect upstream. Science requirements, operations model and lifetime costs are essential from concept exploration through to a critical design review, and are particularly necessary when re-scoping or making trade-off studies. Prototyping and deploying early and often is essential to retire risks and to triage. Science commissioning provides the most insightful testing and uncovers unexpected results. Verification at all levels is essential, with independent quality assurance involvement reporting directly to top management. System engineering is necessary, however it is not sufficient, and is no replacement for thinking and good design. A generalist “floor walker” with broad knowledge of science and telescope elements is needed to ask probing questions at each stage of the project.

9906-77, Session 21

A new 50m class single dish telescope: Large Submillimeter Telescope (LST)

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We report on a new plan to construct a 50m class millimeter and submillimeter single dish telescope, the Large Submillimeter Telescope (LST). The conceptual design and key science of LST will be presented together with its tentative specifications. This telescope is optimized for wide area imaging and spectroscopic surveys in a frequency range of 70 to 420 GHz, which just covers main atmospheric windows at millimeter

and submillimeter wavelengths in good observing sites such as the ALMA site in Chile. We are also aiming at observations at higher frequency up to 1 THz (corresponding to a wavelength of 0.3 mm) with the limited use of the higher-precision inner surface, e.g., with the under-illumination of the surface. The active surface control is needed for correcting gravitational and thermal deformations of the surface, and might be used for the correction of the wind-load deformation. One of the major science goals is unveiling the large-scale structure of high-z universe in 3D and cosmic star formation history with the wide area spectroscopic surveys of dusty starbursts in [CII] and CO lines as well as continuum surveys. With exploiting synergy with ALMA and possibly TMT/SPICA, LST can contribute to the breadth of astronomy and astrophysics; e.g., astrochemistry, star formation in the Galaxy and galaxies, evolution of clusters via the SZ effect, millimeter and submillimeter VLBI, and time-domain science for transients such as GRBs. The surface should have an accuracy of 45 micron (rms) in total or better under a normal nighttime operation condition (when a wind velocity is less than 10 m/s). Ritchey-Chretien optics will be essential in order to achieve a wide field of view of 0.5 deg^2 (up to 1 deg^2) which is required to conduct extremely large area (> a few 100 -- 1000 deg^2a) cosmological deep surveys. The LST will have 3 receiver cabins, i.e., 2 Nasmyth foci and a Cassegrain focus, to accommodate a couple of the proposed state-of-the-art instruments, including wide-field multi-band continuum camera utilizing TES and/or MKID technologies under development in NAOJ and other institutes, large format heterodyne receiver arrays based on the experience of ALMA receiver development in NAOJ, and ultra wide-band multi-object spectrograph whose concept is being tested by DESHIMA and MOSAIC proposed by Delft University of Technology and SRON.

9906-78, Session 21

The next generation very large array

Mark M. McKinnon, Chris L. Carilli, Anthony J. Beasley, National Radio Astronomy Observatory (United States)

Inspired by the ground-breaking results coming from the Atacama Large (sub)Millimeter Array (ALMA), and the Jansky Very Large Array (JVLA), the North American astronomical community is considering a future large area radio array optimized to perform imaging of thermal emission down to milliarcsecond scales. Currently designated the `Next Generation Very Large Array' (ngVLA), such an array would entail ten times the effective collecting area of the JVLA, operate from 1GHz to 115GHz, with ten times longer baselines (300km) providing milliarcsecond resolution, and include a dense core on kilometer scales for high surface brightness imaging. Such an array bridges the gap between ALMA, a superb sub-millimeter array, and the future Square Kilometer Array phase 1 (SKA1-Mid), optimized for a few centimeter and longer wavelengths. The ngVLA opens unique new parameter space in the imaging of thermal emission from cosmic objects ranging from protoplanetary disks to distant galaxies, as well as unprecedented broad band continuum polarimetric imaging of non-thermal processes.

We summarize the design, capabilities, and some of the priority science goals of the ngVLA. As currently envisioned, the continuum resolution of the ngVLA will reach nine milliarcseconds at 1 cm wavelength, with a brightness temperature sensitivity of 6K in one hour. For spectral lines, the array at one arcsecond resolution will reach 0.3K surface brightness sensitivity at 1 cm wavelength and 10 km/s spectral resolution in one hour. These capabilities are the only means with which to answer a broad range of critical scientific questions in modern astronomy, including direct imaging of planet formation in the terrestrial-zone, studies of dust-obscured star formation and the cosmic baryon cycle down to pc-scales out to the Virgo cluster, making a cosmic census of the molecular gas which fuels star formation back to first light and cosmic reionization, and novel techniques for exploring temporal phenomena from milliseconds to years.

We are considering the current VLA site in the high desert plains of the southwest USA as a possible location for the ngVLA. At over 2000m elevation, this region provides good observing conditions for the frequencies under consideration, including reasonable phase stability and opacity at 3mm wavelength over a substantial fraction of the year.

Scientific and technical discussions of the ngVLA are well underway. Science working groups have been formed and are actively refining the ngVLA science case. Two technical workshops have been held to review enabling technologies ranging from antennas, receivers, and correlators to data transmission, time and frequency distribution, and computing architecture. The principal and encouraging conclusion from the workshops is that the technical requirements for achieving a scientifically transformational ngVLA demand only a plausible extrapolation of current technologies.

9906-79, Session 22

The SKA1 low telescope: system architecture and design performance

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The SKA1 Observatory will consist of two radio telescope systems, a low-frequency (50-350 MHz) aperture array in Western Australia, and a mid-frequency (0.35-13.8 GHz) dish array in South Africa. Its scientific objectives will prioritize imaging and spectral observations of the highly red-shifted 21 cm hyperfine line of neutral hydrogen from the Epoch of Reionization and earlier, and will also be well suited for low radio frequency observations of pulsars, magnetized plasmas both in the Galaxy and intergalactic space, radio recombination lines, and potentially extrasolar planets. In addition, a tied-array beamformer and time-domain search engine will be provided to enable pulsar search and timing studies using the tightly concentrated core-area antennas. Development of the SKA1-Low Telescope has been allocated to separate consortia who are responsible for designing the aperture array front end, timing distribution, signal and data transport, correlation and beamforming signal processors, infrastructure, monitor and control systems, and science data processing.

Following a re-scoping activity in 2015, the system has been defined as an array of ~131,000 dual-polarized, log-periodic antenna elements (~512 stations of 256 antennas in a 35m diameter area) arranged in a log-spiral distribution of approximately 40Km radius on the Murchison Radio Observatory site, located at Boolardy Station, Western Australia. The RF signals will be transmitted from the antennas over analog fiber-optic links to a nearby processing facility where the receiver system will directly digitize each antenna signal to process a passband of 50 – 350 MHz, filter into a set of 384 coarse-channels and beamform them at the station level. The packetized data will be routed via a network to an F-X digital correlator and to the pulsar search and timing equipment. Data will be further processed to produce science-ready products at the Pawsey Supercomputing facility, located in suburban Perth, WA. Monitor and control of the telescope components will be provided by a hierarchical, distributed software system enabling automated operation and minimal on-site staffing. This paper will describe the system architectural design and key performance parameters of the telescope in further detail, and summarize the high-level subsystem designs of the consortia.

9906-80, Session 22

Dynamic analysis of DATE5 based on the physically realistic environmental disturbances

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The observation bands of the 5 meter Dome A Terahertz Explorer (DATE5) are primarily over the wavelength of 350 and 200 μm. Thus, the pointing performance of DATE5 require high accuracy. However, the pointing performance of DATE5 is affected by the unsteady wind, which either acts directly on the telescope structure or transmits through the ice and foundation. The main influence of the disturbances acting on the telescope is forces and torques due to wind gusts. Alternating forces and torques cause displacements of the telescope as well as structural oscillations. Both effects lead to pointing errors and therefore have to be compensated as much as possible by the main axes servo controllers. Wind acting on the telescope can be treated as random event, whose expectancy values depends on the specific site. The wind velocity throughout a given time interval can be described as a randomly varying velocity superimposed upon a constant average or mean velocity. For the dynamic analysis, the two components are separated and only the fluctuating component is used. In this paper, the dynamic analysis (mode analysis, harmonic analysis and spectrum analysis) of DATE5 is carried out based on the physically realistic environmental disturbances of dome A. Here, the davenport spectrum of the wind gust, the relation between the gust wind velocity and the wind torque, the power spectrum of wind torque and the telescope response are analyzed and presented in details.

9906-81, Session 22

The Australian SKA Pathfinder: an update

Antony E. Schinckel, Douglas C. Bock, Commonwealth Scientific and Industrial Research Organisation (Australia)

The Australian Square Kilometre Array Pathfinder (ASKAP) will be the fastest dedicated cm-wave survey telescope, and will consist of 36 12-meter 3-axis antennas, each with a large chequerboard phased array feed (PAF) operating from 0.7 to 1.8 GHz, and digital beamformer preceding the correlator. The 96 dual-polarization elements (192 receivers) of the PAF and the subsequent beamformer will provide about 30 beams (at 1.4 GHz) to produce a 30 square degree field of view, allowing rapid, deep all-sky surveys. The large raw data rates involved (~ 100 Tb/sec) and the need to do pipeline processing has led to the antenna incorporating a third axis to fix the parallactic angle with respect to the entire optical system (blockages and phased array feed). It also results in innovative technical solutions to the data transport and processing issues.

ASKAP is located at the Murchison Radio-astronomy Observatory (MRO), a new observatory developed for the Square Kilometre Array (SKA) 315 kilometres north-east of Geraldton, Western Australia. The site was selected through a rigorous process assessing many characteristics, including the RFI “quietness” of the site, which was determined to be outstanding. The MRO will host the initial low frequency instrument of the SKA, “SKA1-LOW”, and the first five years of “lessons learned” at the MRO are informing SKA1-LOW design and operations planning. This observatory is powered by a hybrid power station with a high component of solar sourced power.

Commissioning using six antennas equipped with first-generation phased-array feeds is now complete and CSIRO is in the process of installing second-generation phased-array feeds and receiving systems on all antennas. The Early Science program with the new Mk II PAFs will begin in mid-2016, with a comprehensive science survey program will follow.

ASKAP has attracted over 380 astronomers to join the 10 major survey projects that will form some of the key science projects.

ASKAP is owned and operated by CSIRO as part of the Australia Telescope National Facility (ATNF). The ATNF also includes the Australia Telescope Compact Array (ATCA), the Parkes 64-m Telescope, the Mopra Telescope, and the Murchison Radio-astronomy Observatory, which also hosts ASKAP, EDGES and the Murchison Widefield Array. Recent progress on these other facilities will also be provided.

This scientific work uses data obtained from the Murchison Radio-astronomy Observatory. We acknowledge the Wajarri Yamatji people as the traditional owners of the Observatory site.

9906-82, Session 23

Partially filled aperture interferometric telescopes: achieving large aperture and coronagraphic performance

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Telescopes larger than currently planned 30-m class instruments must break the mass-aperture scaling relationship of the Keck-generation of multi-segmented telescopes. Partially filled aperture, but highly redundant baseline interferometric instruments may achieve both large aperture and high dynamic range. The Colossus design group has explored hybrid telescope-interferometer concepts for narrow-field optical systems.that exhibit coronagraphic performance over narrow fields-of-view. This paper describes how the Colossus and ParFAIT 100m telescope designs achieve 10x lower moving masses than current ELTs.

9906-83, Session 23

Unveiling the dynamic infrared sky with Gattini-IR

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Optical and radio transient surveys are undergoing a renaissance this decade, however, the infrared sky remains virtually unexplored. The fundamental roadblocks in studying the infrared time-domain have been the overwhelmingly bright sky background, limiting the attainable depth per unit time, and the narrow field-of-view of infrared cameras. To address these challenges and opportunities, we present Gattini-IR, a dual hemisphere, infrared-optimized, ultra-wide field high cadence machine. To take advantage of the low sky background at 2.5 um, two identical systems will be located at the polar sites of the South Pole, Antarctica and near Eureka on Ellesmere Island, Canada. Gattini-IR will survey 15,000 sq. degrees to a depth of 20AB, the same depth of the VISTA VHS survey, every 4 hours with a survey efficiency of 97%. Gattini-IR will enable transformative science in areas such as the detection of stellar mergers, core collapse supernovae, binary neutron star mergers, variability of and planetary transit detections around Brown Dwarfs and long term monitoring of dust production from Wolf Rayet Carbon (WC) stars.

9906-84, Session 24

Telescopio San Pedro Martir Observatory preliminary design and project approach

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The Instituto de Astronomia of the Universidad Nacional Autónoma de México (UNAM) along with Instituto Nacional de Astrofisica, Optica y Electronica, the University of Arizona and the Smithsonian Astrophysical Observatory are developing the Telescopio San Pedro Martir (TSPM) project, a 6.5m diameter optical telescope. M3 Engineering & Technology Corp. (M3) is the design and construction management firm responsible for all site infrastructure, enclosure and support facilities.

The Telescopio San Pedro Martir project (TSPM) will be located within the San Pedro Martir National Park in Baja California, Mexico at 2,830 m. above sea level, approximately 65 km. east of the Pacific Ocean, 55km west of the Sea of Cortes (Gulf of California) and 180km south of the United States and México border.

The aim of the paper is to present the preliminary design of the site infrastructure, enclosure and support facilities to date and share the design and construction approach.

Based on the Magellan Telescopes located on Las Campanas, Chile the TSPM enclosure and support facilities design utilizes the successfully proven functional and space organization layout and adapts the design to UNMA's unique requirements and site challenges.

The paper also shares M3's design approach, tools, BIM software used to create the construction documents and the construction method utilizing an engineering, procurement and construction management (EPCM) contract to cost effectively build an observatory on a remote mountain with limited nearby construction resources for a project of this scale and complexity.

9906-85, Session 24

Mechanical conceptual design of 6.5 meter telescope: Telescopio San Pedro Mártir (TSPM)

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Telescopio San Pedro Mártir (TSPM) project intends to build a 6.5 meters telescope with alt-azimuth design, currently completing the preliminary design. The project is an association between Instituto de Astronomía de la Universidad Nacional Autónoma de México (IA-UNAM) and the Instituto Nacional de Astrofísica, Óptica Electrónica (INAOE) in partnership with department of Astronomy and Steward Observatory of University of Arizona and Smithsonian Astrophysical Observatory of Harvard University. Conceptual design of the telescope is lead and developed by the Centro de Ingeniería y Desarrollo Industrial (CIDESI). An overview of the feasibility study and the structural conceptual design are summarized in this paper. The telescope concept is based on telescopes already commissioned such as MMT, and the Baade and Clay Magellan telescopes, building up on these proven concepts. The main differences relative to the Magellan pair are; the elevation axis is located 1 meter above the Primary mirror vertex, allowing for a similar field of view at the Cassegrain and both Nasmyth focal stations; instead of using a vane ends to position the secondary mirror TSPM considers an hexapod like MMT; finally TSPM has a larger floor to m1 cell than its previous cousins. Initially TSPM will operate with a f5 Cassegrain station, but the design considers further Nasmyth configurations from a classical f5 up to a Gregorian. The telescope design includes 7 focal stations: 1 Cassegrain; 2 Nasmyth; and 4 folded-Cassegrain.The telescope will be design and manufactured in Mexico, will be design in Queretaro by CIDESI and built between Queretaro and Michoacán manufacturing facilities; it will be preassembled in these facilities and disassembled to send it to the San Pedro Mártir Observatory for final integration. The azimuth and altitude structure is planned to be constructed in modules and transported by truck and shipped to Ensenada and finally to the OAN where is going to be finally assembled, verified and tested.

9906-86, Session 24

Opto-mechanical design and development status of an all spherical five lenses focal reducer for the 2.4 m Thai National Telescope

Christophe Buisset, National Astronomical Research Institute of Thailand (Thailand); Alexis Deboos, National Astronomical Research Institute of Thailand (Thailand) and Institut d'Optique Graduate School (France); Apirat Prasit, National Astronomical Research Institute of Thailand (Thailand); Thierry Lepine, Institut d'Optique Graduate School (France) and Lab. Hubert Curien (France) and Univ. de Lyon (France); Saran Poshyachinda, Boonrucksar Soonthornthum, National Astronomical Research Institute of Thailand (Thailand)

The 2.4 m Thai National Telescope (TNT) is the main instrument of the Thai National Observatory (TNO) which is located near the summit of the Doi Inthanon, situated in the Chiang Mai Province of Thailand at altitude 2,457 meters. The maximum Field Of View (FOV) covered in 1 exposure is provided by the so-called "4K camera" and is equal to 8.8' x 8.8'square.

The National Astronomical Research Institute (NARIT) is currently developing a focal reducer to image a FOV circular of diameter ?? = 14.6' on the 4K camera with a pixel scale equal to 0.42''/pixel. The spatial resolution will be better than 1.2'' over the full visible spectral domain [400 nm, 800 nm]. The relative irradiance between the ghost and the science images will lower than 0.1%. The maximum distortion will be lower than 1% and the maximum angle of incidence on the filters will be equal to 8 degree.

The design complies with the stringent mechanical and design constrains. First, the position of the 4K camera with and without the focal reducer are similar. Then, the overall dimensions comply with the tiny available volumes. Finally, The optical design comprises only common glasses, only spherical surfaces and the mechanical tolerances can be achieved by using common manufacturing facilities and alignment methods.

The focal reducer comprises 1 doublet L1 located at the fork entrance and 1 triplet L2 located in front of the camera. The doublet L1 will be mounted

on a tip-tilt mount placed on a robotic sliding rail. L1 will thus be placed in the optical path during the observations with the 4K camera and will be removed during the observations with the other instruments. The triplet L2 will be installed on the instrument cube in front of the camera equipped with the filter wheel.

The glass will be manufactured in a specialized company and the mechanical parts will be manufactured by using the NARIT Computer Numerical Control machines. The Lenses will be integrated at NARIT. The verification of the mounting will be performed by using the TNT optical beam simulator currently in development.

The alignment will comprise 4 steps. In a first step, we will measure the in-field variations of the TNT output WFE over a circle of angular diameter equal to 13'. In a second step we will calculate and apply the decentering corrections to the secondary mirror to guaranty the TNT image quality over the specified FOV. The third step will consist of aligning L1 on the elevation axis by using 1 alignment telescope placed at the instrument cube level, 2 targets installed on the TNT elevation axis and 1 target placed on the L1 mount. In a fourth step, we will install the lens L2 on the instrument cube and we will measure the PSF size in-field variations.

Conference 9907: Optical and Infrared Interferometry and Imaging V

Monday - Friday 27–1 July 2016

Part of Proceedings of SPIE Vol. 9907 Optical and Infrared Interferometry and Imaging V

9907-1, Session 1

The Navy Precision Optical Interferometer: an update *(Invited Paper)*

J. Thomas Armstrong, U.S. Naval Research Lab. (United States); Donald J. Hutter, U.S. Naval Observatory (United States); Gerard T. van Belle, Lowell Observatory (United States)

We describe the current status of the Navy Precision Optical Interferometer (NPOI), including developments since the last SPIE meeting. The NPOI group has added stations as far as 250 m from the array center and added numerous infrastructure improvements. Science programs include stellar diameters and limb darkening, binary orbits, Be star disks, exoplanet host stars, and progress toward high-resolution stellar surface imaging. Technical and infrastructure work includes on-sky demonstrations of baseline bootstrapping with five array elements, the VISION beam combiner, and control system updates.

9907-2, Session 1

An update on the CHARA array *(Invited Paper)*

Theo A. ten Brummelaar, Douglas R. Gies, Harold A. McAlister, CHARA (United States); Stephen T. Ridgway, National Optical Astronomy Observatory (United States); Judit Sturmann, Laszlo Sturmann, Gail H. Schaefer, Nils H. Turner, Christopher D. Farrington, Nicholas J. Scott, CHARA (United States); John D. Monnier, Univ. of Michigan (United States); Michael J. Ireland, The Australian National Univ. (Australia)

The CHARA Array, operated by Georgia State University, is located at Mount Wilson Observatory just north of Los Angeles in California. The CHARA consortium includes many groups, including LIESA in Paris, Observatoire de la Cote d'Azur, the University of Michigan, Sydney University, the Australian National University, and the NASA Exoplanet Science Institute. The CHARA Array is a six element optical/NIR interferometer, and for the time being at least, has the largest operational baselines in the world. In this talk I will give a brief introduction to the array infrastructure with a focus on our Adaptive Optics program, and then discuss some of the more recent scientific results coming out of the array.

The AO program is divided into two Phases. Phase I includes wavefront sensors at each telescope and a non-common-path AO system in the laboratory. Phase II will include the DMs for the telescopes. Both phases are fully funded and we expect to complete the program by 2018.

CHARA has a unique imaging capability and so I will focus on results from the MIRC imaging system, including our work on imaging rotating stars and binary stars. A very important part of our work in recent years has been the study of exoplanet host stars - it is as important to know about the star as it is the planet - and I will give a summary of these results. Other highlights will include our recent paper on NOVA Delphini, including the first images of the expanding fireball of a Nova and our recent images of spots on the star Zeta And.

9907-3, Session 1

Overview of LBTI: a multipurpose facility for high spatial resolution observations *(Invited Paper)*

Philip M. Hinz, Denis Defrère, The Univ. of Arizona (United States); Andrew J. Skemer, The Univ. of Arizona (United States); Vanessa Bailey, Stanford Univ. (United States); Jordan Stone, The Univ. of Arizona (United States); Eckhart Spalding, The Univ. of Arizona (United States); Enrico Pinna, Alfio T. Puglisi, Simone Esposito, INAF - Osservatorio Astrofisico di Arcetri (Italy); Oscar Montoya, Elwood Downey, Jarron M. Leisenring, William F. Hoffmann, The Univ. of Arizona (United States); Olivier Durney, John M. Hill, The Univ. of Arizona (United States); Rafael Millan-Gabet, California Institute of Technology (United States); William Danchi, NASA Goddard Space Flight Ctr. (United States); Bertrand Mennesson, Jet Propulsion Lab. (United States); Amali Vaz, Paul Grenz, The Univ. of Arizona (United States); Michael Skrutskie, Univ. of Virginia (United States); Steve Ertel, The Univ. of Arizona (United States)

The Large Binocular Telescope Interferometer (LBTI) is a broad-use facility developed for coherent imaging and nulling interferometry using the 14.4 m baseline of the 2x8.4 m LBT. The unique telescope design, comprising of the dual apertures on a common elevation-azimuth mount, enables some unique interferometric modes. The full system is comprised of dual adaptive optics systems, a near-infrared phasing camera, a 1-5 micron camera (called LMIRcam), and an 8-13 micron camera (called NOMIC). The key program for LBTI is the Hunt for Observable Signatures of Terrestrial planetary Systems (HOSTS), a survey using nulling interferometry to constrain the typical brightness from exozodiacal dust around nearby stars. Additional observations focus on the detection and characterization of giant planets in the thermal infrared, and high spatial resolution imaging of complex scenes such as Jupiter's moon, Io, or forming planets in transition disks. Currently upgrades are underway for doubling the LMIRcam field size from 10 to 20 arcseconds, improving the AO performance and limiting magnitude, adding an integral field spectrometry mode, and tracking path length dispersion due to water vapor. We present the current performance of LBTI, an overview of the upgrades, and the driving science cases for the new LBTI capabilities.

9907-4, Session 2

A new path to first light for the Magdalena Ridge Observatory Interferometer *(Invited Paper)*

Michelle J. Creech-Eakman, Ifan Payne, Van Romero, New Mexico Institute of Mining and Technology (United States); Christopher A. Haniff, David F. Buscher, John S. Young, Univ. of Cambridge (United Kingdom)

The Magdalena Ridge Observatory Interferometer (MROI) was the most ambitious IR interferometric facility conceived of in 2003 when funding began. Today, despite having suffered some financial short-falls, it is still one of the most ambitious interferometric imaging facilities ever

designed. With an innovative approach to attaining the original goal of fringe tracking to H = 14th magnitude via completely redesigned mobile telescopes, and a unique approach to the beam train and delay lines, the MROI will be able to image faint and complex objects with milliarcsecond resolutions for a fraction of the cost of giant telescopes or space-based facilities. The design goals of MROI have been optimized for studying stellar astrophysical processes such as mass loss and mass transfer, the formation and evolution of YSOs and their disks, and the environs of nearby AGN.

The global needs for Space Situational Awareness (SSA) have moved to the forefront in many communities as Space becomes a more integral part of a national security portfolio.

These needs drive imaging capabilities ultimately to a few tens of centimeter resolution at geosynchronous orbits. Any array capable of producing images on faint and complex geosynchronous objects in just a few hours will be outstanding not only as an astrophysical tool, but also for these types of SSA missions. With the recent infusion of new funding from the Air Force Research Lab (AFRL) in Albuquerque, NM, MROI will be able to attain first light, first fringes, and bootstrapping with three telescopes by 2020.

MROI's current status along with a detailed sketch of our activities over the coming 5 years will be presented, as well as clear opportunities to collaborate on various aspects of the facility as it comes online. Further funding is actively being sought to accelerate the capability of the array for interferometric imaging on a short time-scale so as to achieve the original goals of this ambitous facility.

The MRO Interferometer is supported through AFRL Cooperative Agreement, FA 9453-15-2-0086 and via the generous support of the Congressional Delegation of the State of New Mexico.

9907-5, Session 2

The 2nd generation VLTI roadmap to performance *(Invited Paper)*

Julien Woillez, Jean-Philippe Berger, Sebastian Egner, Frédéric Yves J. Gonté, European Southern Observatory (Germany); Pierre Haguenauer, Antoine Mérand, European Southern Observatory (Chile); Lorenzo Pettazzi, Markus Schöller, European Southern Observatory (Germany); Nicolas Schuhler, European Southern Observatory (Chile)

By mid-2016, the upgrade of the basic VLTI infrastructure will be completed with the transformation of the laboratory and installation of star separators on both the 1.8-m Auxiliary Telescopes, and the 8-m Unit Telescopes. The GRAVITY fringe tracker will have had a full semester of commissioning on the ATs, and a first look on the UTs. The CIAO infrared wavefront sensor will start demonstrating its performance relative to the visible wavefront sensor MACAO. First astrometric measurements on the ATs and astrometric qualification of the UTs will be on-going. This will be a good time to revisit the VLTI roadmap initiated in 2014.

This VLTI roadmap aims at developing the infrastructure in order to provide functionalities and performances compatible with the new generation of instruments: GRAVITY and MATISSE. This contribution will provide a summary of the current performance, the improvements planned for the next three years, the limitations, and the latent potentials of VLTI.

This contribution focuses on the mid-range future of VLTI. It aims at stimulating a reflection on where we, as a community, want to take VLTI. It is complementary to F. Gonté's presentation covering what was recently accomplished, as part of the VLTI shutdown: the infrastructure upgrade in preparation to the arrival of Gravity, CIAO, and Matisse.

9907-6, Session 3

First light for GRAVITY *(Invited Paper)*

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GRAVITY is the new VLTI instrument for precision narrow-angle astrometry and interferometric phase referenced imaging of faint objects. With its fibre-fed integrated optics, sub-electron readnoise fringe tracker, active beam stabilization and a novel three-beam metrology concept, GRAVITY will push the sensitivity and accuracy far beyond what is offered today. The instrument has seen first light with the four 1.8m Auxiliary Telescopes in fall 2015, and we are expecting first light with the four 8m Unit Telescopes in time for the conference. In our presentation we will give an overview of the instrument and we will present its current performance and the plans for the upcoming science exploration.

9907-7, Session 3

First results on-sky of the GRAVITY integrated optics beam combiners

Laurent Jocou, Karine Perraut, Jean-Baptiste Le Bouquin, Institut de Planétologie et d'Astrophysique de Grenoble (France); Pierre Kervella, Observatoire de Paris (France); Vincent Lapeyrère, Observatoire de Paris à Meudon (France); Oliver Pfuhl, Max-Planck-Institut für extraterrestrische Physik (Germany); Sylvain Guieu, Institut de Planétologie et d'Astrophysique de Grenoble (France); Pierre R. Labeye, CEA-LETI (France); Jean-Philippe Berger, Institut de Planétologie et d'Astrophysique de Grenoble (France); Sylvestre Lacour, Observatoire de Paris à Meudon (France); Marcus Haug, Andreas Pflüger, Frank Eisenhauer, Max-Planck-Institut für extraterrestrische Physik (Germany); Guy S. Perrin, Observatoire de Paris à Meudon (France); António Amorim, Fundacão da Faculdade de Ciências da Univ. de Lisboa (Spain); Wolfgang Brandner, Max-Planck-Institut für Astronomie (Germany); Christian Straubmeier, Univ. zu Köln (Germany)

GRAVITY is the VLTI second generation instrument operating in the K band that aims at studying physics close to the Galactic Centre black hole. The beam combiner instrument obtained its first fringes on sky in November 2015, giving a first promising trend of the instrument performance. This first commissioning and the next ones planned in the beginning of 2016 will allow to fully validate the performance in real conditions of the two integrated optics beam combiners at the heart of GRAVITY. After a brief recall of the concept of the integrated optics devices, we will present their characterization results obtained during the commissioning runs.

9907-8, Session 3

Dual field interferometry with GRAVITY: the largest optical telescope in the world opens its second eye

Oliver Pfuhl, Max-Planck-Institut für extraterrestrische Physik (Germany) and European Southern Observatory (Chile); Frank Eisenhauer, Max-Planck-Institut für extraterrestrische Physik (Germany); Guy S. Perrin, Observatoire de Paris à Meudon (France); Karine Perraut, Institut de Planétologie et d'Astrophysique de Grenoble (France); Antonio Amorim, Fundacão da Faculdade de Ciências da Univ. de Lisboa (Portugal); Christian Straubmeier, Univ. zu Köln (Germany); Sylvestre Lacour, Observatoire de Paris à Meudon (France); Stefan Gillessen, Max-Planck-Institut für extraterrestrische Physik (Germany); Wolfgang Brandner, Max-Planck-Institut für Astronomie (Germany); Senol Yazici, Magdalena Lippa, Thomas Ott, Marcus Haug, Ekkehard Wieprecht, Reinhard Genzel, Max-Planck-Institut für extraterrestrische Physik (Germany)

We recently commissioned the dual field mode of GRAVITY. This mode uses one object to track and stabilize fringes allowing for coherent integration times of the order 100s on a second faint object. The first object pair where this was successfully demonstrated was a mK ~ 4.5 fringe-tracking star and a mK ~ 8.5 science object observed at a spectral resolution of 500. The dual field mode opens uncharted territory in interferometry. It allows interferometric observations of objects about 5 magnitudes fainter that the current limit with up to 4000 spectral resolution in K-band. In combination with the dedicated laser metrology it provides phase-referenced imaging on 6 baselines. Furthermore it is the key for the envisioned 10 micro-arcsecond dual-field astrometry. The primary science driver of GRAVITY is the capability of astrometry. The system is designed to measure accretion dynamics and relativistic effects in the vicinity of the Galactic Center black hole. The implementation of the dual field mode is a big leap towards that goal. I will introduce the technology, present the latest scientific achievements and discuss challenges and future prospects of dual field interferometry.

9907-9, Session 3

An overview of the mid-infrared spectro-interferometer MATISSE: science, concept, and current status *(Invited Paper)*

Alexis Matter, Bruno Lopez, Observatoire de la Côte d'Azur (France)

MATISSE is the second generation mid-infrared spectrograph and imager for the Very Large Telescope Interferometer (VLTI) at Paranal. This new interferometric instrument will allow significant advances by opening new avenues in various fundamental research fields: studying the planet-forming region of disks around young stellar objects, understanding the surface structures and mass loss phenomena affecting evolved stars, and probing the environments of black holes in active galactic nuclei. As a first breakthrough, MATISSE will enlarge the spectral domain of current optical interferometers by offering the L & M bands in addition to the N band. This will open a wide wavelength domain, ranging from 2.8 to 13 ?m, exploring angular scales as small as 3 mas (L/M band) / 10 mas (N band). As a second breakthrough, MATISSE will allow mid-infrared imaging - closure-phase aperture-synthesis imaging - with up to four Unit Telescopes (UT) or Auxiliary Telescopes (AT) of the VLTI. Moreover, MATISSE will offer a spectral resolution range between R~30 to ~5000. Here, we present one of the main science objectives, the study of protoplanetary disks, that drives the instrument design and has motivated several VLTI upgrades (GRA4MAT & NAOMI). We introduce the physical concept of MATISSE including a description of the signal on the detectors and an evaluation of the expected performances. We also discuss the current status of the MATISSE instrument, which is entering its testing phase, and the foreseen schedule for the next two years that will lead to the first light at Paranal.

9907-10, Session 3

Imaging capabilities of the VLTI/MATISSE spectra-interferometric instrument *(Invited Paper)*

Joel Sanchez, Jörg-Uwe Pott, Thomas Henning, Roy van Boekel, Max-Planck-Institut für Astronomie (Germany); Bruno Lopez, Alexis Matter, Observatoire de la Côte d'Azur (France); Fabien Baron, Georgia State Univ. (United States); Florentin Millour, Observatoire de la Côte d'Azur (France); Gerd Weigelt, Karl-Heinz Hofmann, Dieter Schertl, Max-Planck-Institut für Radioastronomie (Germany)

During the last decade, the first generation of beam combiners at the Very Large Telescope Interferometer has proved the importance of optical interferometry for high-angular resolution astrophysical studies in the near- and mid-infrared. With the advent of 4-beam combiners at the

VLTI, the u-v coverage per pointing increases significantly, providing an opportunity to use reconstructed images as powerful scientific tool.

We present studies to characterize the imaging capabilities of the Multi-AperTure mid-infrared SpectroScopic Experiment (MATISSE), a second generation instrument for the Very Large Telescope Interferometer (VLTI). Its six-baselines, optics and high-spectral resolution (R~5000) will deliver for the first time thermal-IR interferometric data with enough u-v coverage and differential phase information for imaging. In this work, we report detailed image reconstruction studies carried out with four image reconstruction packages: PAINTER, MIRA, IRBIS and SQUEEZE. For our studies, we use realistic simulated MATISSE data from radiative transfer simulations of two astrophysical objects: a proto-planetary disk and the surface of a giant star with hot-spots. In particular, we will discuss the roles of the regularization function, u-v coverage, and of the initial brightness distribution. MATISSE will perform observations at three different mid-infrared bands: L, M and N. Hence, due to its large bandwidth, chromatic effects should be taken into account when image reconstruction is attempted. We will also discuss the capabilities of the different packages to perform multi-wavelength image reconstruction. Finally, we discuss the implementation of Compress Sensing to recover interferometric images, a technique that has demonstrated fruitful results to restore signals from data with missing information and that has recently demonstrated its applicability to image reconstruction in current and future radio interferometers (e.g., LOFAR, SKA). Since it has been barely tested with the optical ones, we explore the performance of interferometric imaging using Compress Sensing in the context of the upcoming interferometric instrumentation. The work here presented is being carried out within the Opticon FP7-2 joint research activity on interferometric imaging.

9907-11, Session 3

MATISSE: integration and test phase first results

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MATISSE (Multi AperTure mid-Infrared SpectroScopic Experiment) is the spectro-interferometer of the European Southern Observatory VLT operating in the spectral bands L, M and N, and combining up to four beams from the unit or the auxiliary telescopes. MATISSE will offer new breakthroughs in the study of circumstellar environments by allowing the mapping of the material distribution, the gas and essentially the dust.

The instrument consists in a warm optical system (WOP) accepting four beams from the VLTI and relaying them after a dichroic splitting (for the L/M- and N- spectral bands) to cold optical benches (COB) located in two separate cryostats. The Observatoire de la Côte d'Azur is in charge of the WOP providing the functions of spectral band separation, optical path equalization and modulation, pupil positioning, beam anamorphosis, beam commutation, and calibration. NOVA-ASTRON is in charge of the COB providing the functions of beam selection, reduction of thermal background emission, spatial filtering, pupil transfer, photometry and interferometry splitting, additional beam anamorphosis, spectral filtering, polarization selection, image dispersion, and image combination. The Max Planck Institut für Radioastronomy is in charge of the operation and performance validation of the two detectors, a HAWAII-2RG from Teledyne for the L/M-band and a Raytheon AQUARIUS for the N-band, provided by the European Southern Observatory. The Max Planck Institut für Astronomie is in charge of the cryostats for which the requirements on space limitations and vibration stability resulted on very specific choices on the design.

The integration and test of the two cryogenic systems, including the cold benches and detectors, have been conducted at MPIA in parallel with the integration of the WOP at OCA. At the end of 2014, the complete instrument was integrated at OCA. Following the integration, a period of interface and alignment took place resulting in the first interference fringes in the L-band during summer 2015.

After a period of optimization of both the instrument reliability and the environmental working conditions, the test plan is presently being conducted in order to evaluate the complete performance of the instrument and its compliance with the high-level requirements.

The present paper gives the first results of the integration and tests of the MATISSE instrument.

9907-12, Session 4

Imaging protoplanets: observing transition disks using non-redundant masking *(Invited Paper)*

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Transition disks provide an opportunity to study planet formation in situ. While explaining these inner clearings is a challenge, young planets accreting material that would have otherwise fallen onto the star likely play a major role. The novel imaging technique of non-redundant masking (NRM) can achieve the angular resolution and contrast needed to detect forming planets within known transition disk gaps. NRM transforms a filled aperture into an interferometric array through the use of a pupil plane mask, allowing for better point-spread function characterization than even an adaptive-optics-corrected telescope and expanding the observable companion parameter space. We present new NRM+AO observations of the T Cha and LkCa 15 transition disks. We also re-analyze archival data from the VLT and Keck, performing new and statistically rigorous error analysis. T Cha hosts a posited substellar companion detected in single-epoch NRM observations taken at the Very Large Telescope (VLT). However, multi-epoch datasets from both the VLT and the Magellan Adaptive Optics system (MagAO) show a lack of orbital motion and are incompatible with a companion orbiting in the plane of the outer disk. A model based on forward scattering from the edge of the outer disk is more consistent with the observations. Conversely, NRM observations of LkCa 15 taken at the Large Binocular Telescope confirm the structure seen in previous observations, and suggest multiple forming planets. We detect three infrared point sources within the disk clearing. Orbital fits to these

and re-analyzed archival Keck NRM data show that the source positions are consistent with distinct Keplerian orbits. The observed infrared fluxes agree with theoretical predictions for circumplanetary disks and are inconsistent with those expected for hot-start models. We also detect one of the infrared sources in new MagAO H-alpha observations, tracing hot (~10,000 K) gas falling deep into the potential well of a protoplanet. We discuss the characteristics of this forming planetary system and its implications for future planet formation studies.

9907-13, Session 5

Single aperture interferometry: masking and beyond *(Invited Paper)*

Peter G. Tuthill, Univ. of Sydney (Australia)

Interferometric techniques developed to recover information up to and beyond the diffraction limit of a large telescope aperture have a long and successful pedigree. Stretching back to the dawn of interferometry itself, Fizeau's original 1867 proposal to measure stellar sizes is the genesis of our entire field. The startlingly durable technique he proposed - going by several modern names including aperture masking, SAM and NRM, thrives today nearly 150 years later, unaltered in basic principles. It continues to produce unique science, flouting all reasonable expectations for experimental longevity. New approaches inspired by these successes have branched in many exciting directions including a coming generation of photonic interferometers which reformulate the underlying ideas in a format exploiting guided-wave optics.

This invited review will cover the history and present science being accomplished with aperture masking interferometry. This spans the astrophysical spectrum from young stars to evolved, and from exoplanets to supergiants. Further advances and refinements to the technique are presently showing enormous promise. This talk will discuss kernel phase interferometry, pupil fragmentation and remapping techniques, refinements such as interferometric polarimetry and other differential approaches, as well as interferometry from space platforms such as JWST.

9907-14, Session 5

VAMPIRES: a polarimetric non-redundant-masking interferometer for diffraction-limited imaging of dusty circumstellar environments

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The direct imaging of the process of solar system formation, where planets are formed within a protoplanetary disk, can potentially resolve many mysteries in this poorly understood process. Along with imaging the dusty atmospheres of evolved stars, these observations pose a huge technical challenge due to the high angular-resolutions and contrasts required. The major stumbling block is the problem of the Earth's own atmospheric turbulence. One solution to this problem is aperture masking interferometry, which transforms the pupil of a single 8 m class telescope into an interferometric array of smaller sub-pupils by way of a mask placed in the telescope's pupil plane. The other difficulty is that precise calibration is required to combat the extremely high contrast ratios and high resolutions faced. By taking advantage of the fact that starlight scattered by dust in the circumstellar region is polarised, differential polarimetry can be used to achieve this calibration, as well as making polarimetric measurements.

VAMPIRES (Visible Aperture Masking Polarimetric Interferometer for Resolving Exoplanetary Signatures) is a newly commissioned high-angular resolution imager which capitalises on these techniques. Developed by the University of Sydney in conjunction with the SCExAO extreme adaptive-optics project, it is currently deployed on the Subaru telescope as part of the SCExAO system.

In contrast to conventional coronagraphic techniques, aperture masking interferometry has demonstrated the ability to image faint companions at resolutions well beyond the diffraction limit. VAMPIRES leverages this technique in combination with polarimetry, to directly image structure in the inner-most regions of protoplanetary systems and evolved stars, at visible wavelengths. VAMPIRES uses starlight scattered by dust in the inner region of such systems to precisely map the disks, shell, gaps, knots and waves that are key to understanding disk evolution and planet formation, along with the mass-loss process of dying stars. With a spatial resolution of ~10 mas and with a maximum field of view of ~500 mas, VAMPIRES perfectly compliments coronagraphic observations in the near-IR, and in fact can operate simultaneously with IR coronagraphic observations by utilising the otherwise unused visible wavelengths. High resolutions and dynamic ranges are enabled by VAMPIRES' triple-layered polarimetric differential calibration system, using simultaneous polarised channel splitting, fast liquid-crystal channel switching and half-wave-plate based channel switching. Multiple opto-mechanical systems allow various aperture-masks, polarisation devices and imaging subsystems to be deployed, with the final interferogram imaged at high cadence using an EMCCD detector.

Now commissioned on-sky, VAMPIRES has demonstrated polarised differential visibility precisions of 1 part in 1000, and differential closure phases of a fraction of a degree. The instrument has recently produced its first science results, resulting in milliarcsecond, high-contrast imaging of dusty circumstellar regions.

9907-15, Session 5

FIRST-IR instrument: latest development and results of nulling capabilities

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In the context of direct detection of exoplanets and disks, the use of high angular resolution and high contrast techniques is essential. The issue is to detect the light from a companion located at a small angular separation from its parent star and at the same time to deal with the high difference

of their respective luminosity.

FIRST-IR (Fibered Instrument foR a Single Telescope) is an interferometric instrument developed at the Observatoire de Paris-Meudon (LESIA) to fulfill the aforementioned requirements. This demonstrator is operating in the near infrared (H band: $lambda=1.65 mu m$) and leans upon pupil remapping using single mode fibers and integrated optic for recombination.

Pupil remapping derives from sparse aperture masking, transforming the pupil of the telescope into a interferometric array, but pushes the concept further, aiming at making interfere every sub-division of the main pupil, two by two. This allows to get rid of non-coherent addition of the perturbed wavefront due to redundancy in the pupil.

The light from each sub-pupil is injected into its respective fiber, dispatching it into the integrated optic beam combiner.

Integrated optics, originally developed for telecommunications were implanted successfully in astronomy. The PIONIER instrument at the VLTI and the soon-coming GRAVITY instrument are perfect examples of the strong potential of such devices. They offer an advantageous technical solution that is stable and compact and easy to integrate in an instrument for the recombination of light.

They consist of a substrate on which waveguides are engraved and whose disposition and geometry allow multiple configurations of recombination. The information on the phase delay between the input beams is coded in the outputs of the integrated optic: the intensity of interference fringes are sampled on a quadruplet of pixels for each pair of recombined sub-pupils.

In this study, we present the current state of the FIRST-IR instrument which combines pupil remapping with nulling to cancel the stellar light, and thus decrease the photon noise outshining the light from the companion. We will present the first light results of this prototype component, in particular the closure phase signal after nulling

9907-16, Session 6

The Dragonfly interferometer: on-sky demonstration of a photonic pairwise beam combiner with on-chip pupil reformatting using hybridized 2D-3D architecture

Nick Cvetojevic, The Univ. of Sydney (Australia) and Australian Astronomical Observatory (Australia); Barnaby R. Norris, The Univ. of Sydney (Australia); Simon Gross, Alexander Arriola, Macquarie Univ. (Australia); Takayuki Kotani, National Astronomical Observatory of Japan (Japan); Sylvestre Lacour, Observatoire de Paris à Meudon (France); Michael J. Withford, Macquarie Univ. (Australia); Jonathan S. Lawrence, Australian Astronomical Observatory (Australia); Peter G. Tuthill, The Univ. of Sydney (Australia)

Aperture masking, wherein the pupil of a single large telescope is divided into a number of sub-apertures, has a proven track record in enabling diffraction-limited imaging and high contrast detections on seeing-limited 8m class telescopes. However only a small fraction of the telescope's total aperture can be used this way, since the holes must be arranged in a non-redundant configuration, and variations in phase across the sub-apertures due to atmospheric fluctuations introduce closure-phase error.

A newer technique is pupil remapping, wherein the holes in the mask are replaced by a number of single mode optical waveguides. This offers a number of advantages: firstly, the arrangement of the waveguide's inputs at the pupil plane need not be non-redundant, hence a large portion of the telescope's aperture can be used. Secondly, the single-mode nature of the waveguides means the phase is flat across each sub-aperture, allowing precise closure phases to be measured. Thirdly, the 2D input pattern can be remapped to 1D output, allowing the use of an integrated photonic chip based beam combiner.

The Dragonfly instrument is a photonic pupil remapping interferometer, utilizing a hybridized 2D-3D architecture to perform the injection, remapping, and on-chip beam combination, all on a single self-contained structure. The current iteration of the Dragonfly chipset consists of an 8-port pairwise beam combiner, which combines all 28 possible baselines in quadrature on-chip, outputting 112 flux channels from which the visibilities and phases of the fringes are extracted, and a further 8 photometric taps allowing the time-varying, asymmetric input coupling to be calibrated for (resulting in significantly improved visibility calibration). To remap the telescope pupil to the 8 input ports of the beam combiner chip, a series of waveguides are manufactured in three dimensions within a block of glass, using ultrafast laser inscription, and directly bonded with the beam-combining chip forming a single monolithic device. Due to the short coherence length of the starlight (~ 10 microns for a typical NIR bandpass) the path lengths of each waveguide must be matched to micron precision. One advantage of Dragonfly's approach is that the path lengths of waveguides within the chip are extremely robust against changes in optical path length from the environment. Further, a series of side-steps and masks are integrated to remove the impact of stray-light. Lastly, a micro-lens array is bonded to the input of the chipset, matching the waveguide array that segments the pupil. The Dragonfly chipset requires no ongoing alignment between any of the photonic components, making the device far more robust even under a changing gravity vector (cassegrain deployment), and only requires that the telescope pupil be aligned to the input of the chip, achieved using a single translation stage, greatly reducing the complexity of implementing photonic interferometers.

Here, we present results from the recent Dragonfly commissioning run on the 3.9 m Anglo-Australian Telescope, along with the latest performance measurements from our laboratory testbed. When wavefront error above 2pi radians is applied to an input waveguide, closure phase RMS of 0.9 degrees is obtained.

9907-17, Session 6

New results with aperture masking interferometry from Keck and VLT: discovery of scaled-up exoplanets?

Sasha Hinkley, Univ. of Exeter (United Kingdom); Adam L. Kraus, The Univ. of Texas at Austin (United States); Michael J. Ireland, The Australian National Univ. (Australia); Anthony C. Cheetham, The Univ. of Sydney (Australia); John M. Carpenter, California Institute of Technology (United States); Peter G. Tuthill, The Univ. of Sydney (Australia); Sylvestre Lacour, Observatoire de Paris à Meudon (France); Thomas M. Evans, Univ. of Exeter (United Kingdom); Xavier Haubois, The Univ. of Sydney (Australia)

We report the detection of seven low-mass companions to intermediate-mass stars in the Scorpius–Centaurus (Sco–Cen) Association using non-redundant aperture masking interferometry at Keck and VLT. Our newly detected objects have L-band contrasts 4–6 magnitudes fainter than their host star, corresponding to masses as low as 20 Jupiter masses and mass ratios as small as 1%, depending on the assumed age of the target stars. With projected separations of 10–30 AU, our aperture masking detections sample an orbital region totally out of reach to previous, conventional adaptive optics imaging of intermediate-mass Sco–Cen stars that covered much larger orbital radii (30–3000AU). At such orbital separations, these objects resemble higher-mass versions of the directly imaged planetary mass companions to the 10–30 Myr, intermediate-mass stars HR 8799, beta Pictoris, and HD 95086. These newly discovered companions span the brown dwarf desert, and their masses and orbital radii provide a new

constraint on models of the formation of low-mass stellar and substellar companions to intermediate-mass stars.

9907-18, Session 7

Speckle imaging at large telescopes: current results and future prospects
(Invited Paper)

Elliott P. Horch, Southern Connecticut State Univ. (United States)

The development of electron-multiplying CCD cameras (EMCCDs) has changed the landscape and prospects for speckle imaging in recent years. These detectors have quantum efficiencies above 90% through most of the visible range and effective read noise of much less than one electron when the electron-multiplying gain amplifier is used. They are, therefore, effectively photon-counting devices with nearly maximal collection of photons. In addition, the best commercially available devices have low dark current and yet are very easy to use, requiring no liquid nitrogen cooling. Compared with intensified-CCDs more traditionally used in speckle work, they have much greater sensitivity and read out at approximately the same speed. These properties make them extremely efficient devices for speckle imaging, and their use in this application has allowed for progress in certain problems in high-resolution imaging in the single-aperture regime, including in searching for faint stellar companions near exoplanet host stars and in satellite imaging. Crucial to the science in both of these applications is the photometric linearity of the devices in the context of speckle imaging; this has now been demonstrated by multiple teams of observers.

This situation has led to an increased and more consistent use of speckle imaging at mid-sized and large telescopes. Most notably, there are now speckle visitor instrument programs that use EMCCDs available to the community at several observatories throughout the world including the Gemini North and Gemini South telescopes and the WIYN telescope at Kitt Peak National Observatory. Both the SOAR telescope in Chile and Special Astrophysical Observatory 6-m telescope in Russia have speckle cameras in their suite of permanent instruments. A new community of users has responded to this availability and is using these cameras for a range of astronomical observations. An overview of the science applications will be described, and some results of these efforts will be discussed. The outlook for the future of speckle imaging will be given, in three main areas: (1) the development of future instrumentation, (2) prospects for more robust image reconstruction algorithms, and (3) scientific problems that could benefit from these developments, including those that could involve the combined use of both speckle and other high-resolution techniques.

9907-19, Session 7

SRAO: the southern robotic speckle + adaptive optics system

Nicholas M. Law, Carl Ziegler, The Univ. of North Carolina at Chapel Hill (United States); Andrei Tokovinin, National Optical Astronomy Observatory (Chile)

We will present plans for SRAO, the first Southern Robotic AO system. SRAO, based at the 4m SOAR telescope, will use AO-assisted speckle imaging and Robo-AO-heritage high efficiency observing to confirm and characterize thousands of planet candidates produced by major new transit surveys like TESS. SRAO is the first AO system to have the resolution and efficiency to build a comprehensive several-thousand-target multiplicity survey at sub-AU scales across the main sequence. We will also describe results from Robo-AO, the first robotic LGS-AO system. Robo-AO has observed tens of thousands of Northern targets, often using a similar speckle or Lucky-Imaging assisted mode.

SRAO will be a "moderate-order" natural-guide-star adaptive optics system which uses an innovative photon-counting wavefront sensor and EMCCD speckle-imaging camera to guide on faint stars with the 4.1m SOAR telescope. The system will produce diffraction-limited imaging in the NIR on targets as faint as mV=16. In AO-assisted speckle imaging mode the system will attain the 30-mas visible diffraction limit on targets at least as faint as mV=17. The system will be the first Southern hemisphere robotic adaptive optics system, with overheads an order of magnitude smaller than comparable systems. Using Robo-AO's proven robotic AO software, SRAO will be capable of sub-minute observing overheads, allowing the observation of at least 200 targets per night. SRAO will attain three times the angular resolution of the Palomar Robo-AO system in the visible, and will complement the ongoing Northern Kitt Peak Robo-AO survey.

9907-20, Session 8

The role of Fizeau interferometry in solar system studies

Albert R. Conrad, Large Binocular Telescope Observatory (United States)

Historically, two types of interferometer have been applied to the study of solar system objects: coaxial and Fizeau. While coaxial interferometers are well-suited to a wide range of galactic and extra-galactic science cases, solar system science cases are, in most cases, better carried out with Fizeau imagers. Targets of interest in our solar system are often bright and compact, and the science cases for these objects often call for a complete, or nearly complete, image at high angular resolution. For both methods, multiple images must be taken at varying baselines to reconstruct an image. However, with the Fizeau technique that number is far fewer than it is for the aperture synthesis method employed by co-axial interferometers.

In our solar system, bodies rotate and their surfaces are sometimes changing over yearly, or even weekly, time scales. Thus, the need to be able to exploit the high angular resolution of an interferometer with only a handful of observations taken on a single night, as is the case for Fizeau interferometers, gives a key advantage to this technique.

The aperture of the Large Binocular Telescope (LBT), two 8.4 circular mirrors separated center-to-center by 14.4 meters, is optimal for supporting Fizeau interferometry. The first of two Fizeau imagers planned for LBT, the LBT Interferometer (LBTI), saw first fringes in 2010 [Hinz et al, SPIE, 2012] and has proven to be a valuable tool for solar system studies. Recent studies of Jupiter's volcanic moon Io have yielded results that rely on the angular resolution provided by the full 23-meter baseline of LBT [Leisenring et al, SPIE, 2014; Conrad et al, AJ, 2015; Skrutskie et al, Icarus, in prep]. Future studies of the aurora at Jupiter's poles and the shape and binarity of asteroids are planned.

While many solar system studies can be carried out on-axis (i.e., using the target of interest as the beacon for both adaptive optics correction and fringe tracking), studies such as Io-in-eclipse, full disk of Jupiter and Mars, and binarity of Kuiper belt objects, require off-axis observations (i.e., using one or more nearby guide-moons or stars for adaptive optics correction and fringe tracking). These studies can be plagued by anisoplanatism, or "cone effect." LINC-NIRVANA (LN), the first multi-conjugate adaptive optics system (MCAO) on an 8-meter class telescope in the northern hemisphere, provides a solution to the ill-effects of anisoplanatism. Longer term, an upgrade planned for LN will establish its original role as the second LBT Fizeau imager. The full-disk study of several solar system bodies, most notably large and/or nearby bodies such as Jupiter and Mars which span tens of arcseconds, would be best studied with LN.

We will review the past accomplishments of Fizeau interferometry with LBTI, present plans for using that instrument for future solar system studies, and, lastly, explore the unique solar system studies that require the LN MCAO system combined with Fizeau interferometry.

9907-21, Session 9

Intensity interferometry: optical imaging with kilometer baselines *(Invited Paper)*

Dainis Dravins, Lund Observatory (Sweden)

Microarcsecond resolution imaging requires multi-element and kilometer-scale interferometers operated at their diffraction limit. However, the high stability requirements for measuring first-order optical coherence with amplitude and phase interferometers limit the construction of such complexes on either the ground or in space. Intensity interferometry, correlating intensity fluctuations between independent telescopes to measure the second-order optical coherence, circumvents atmospheric turbulence and is immune to telescopic imperfections. Telescopes are connected only electronically (rather than optically), and the error budget relates to electronic timescales of perhaps a few nanoseconds (light-travel distance on the order of a meter), enabling observations at short optical wavelengths (even through large airmasses far from zenith), as well as the use of optically imperfect telescopes. Once pioneered by Hanbury Brown and Twiss, this two-photon method is generally seen as the first quantum optics experiment. As a modern digital technique, it has now been demonstrated with arrays of small laboratory telescopes, observing artificial stars over hundreds of optical baselines, reconstructing diffraction-limited images. With telescopes linked only by electronic software, the technique can readily be expanded to large arrays, analogous to current radio interferometers. Baselines of a few km will provide resolutions in visual light on tens of microarcseconds, adequate for viewing details on stellar surfaces or perhaps even the silhouettes of transiting exoplanets. However, as shown in numerical simulations, observations are currently practical only for bright and hot objects (such as naked-eye stars hotter than the Sun); fainter targets will be reached once suitable photon-counting and energy-resolving detectors become available.

In this review, an overview of the method is given from its beginnings some 50 years ago; its later non-astronomical applications in high-energy particle physics; current optical experiments by various groups, and the prospects for future observations using either the large arrays of optical air Cherenkov telescopes now under construction for primarily gamma-ray studies, or on extremely large single-aperture telescopes.

9907-22, Session 9

Intensity interferometry with Aqueye+ and Iqueye in Asiago

Luca Zampieri, INAF - Osservatorio Astronomico di Padova (Italy); Giampiero Naletto, Carlo Barbieri, Univ. degli Studi di Padova (Italy); Mauro Barbieri, Univ. of Atacama (Chile); Enrico Verroi, Gabriele Umbriaco, P. Favazza, Univ. degli Studi di Padova (Italy); Luigi Lessio, Giancarlo Farisato, INAF - Osservatorio Astronomico di Padova (Italy)

Since a number of years our group is engaged in the design, construction and operations of instruments with very high time resolution in the optical band for applications to Quantum Astronomy and more conventional Astrophysics. Two instruments were built to perform photon counting with sub-nanosecond temporal accuracy. The first of the two, Aqueye+, is regularly mounted at the 1.8m Copernicus telescope in Asiago, while the second, Iqueye, was mounted at the NTT telescope in Chile, and at the WHT and TNG telescopes on the Roque (La Palma, Canary Islands). Both instruments deliver extraordinarily accurate results in optical pulsar timing.

Recently, Iqueye was moved to Asiago to be mounted at the 1.2m Galileo telescope to attempt, for the first time ever, experiments of optical intensity interferometry (à la Hanbury Brown and Twiss) on a baseline of a few kilometers. This application was one of the original goals for the development of our instrumentation. To carry out these measurements, we are experimenting a new way of coupling the instruments to the telescopes, by means of moderate-aperture, low-optical-attenuation multi-mode optical fibers with a double-clad design. Fibers are housed in dedicated optical interfaces attached to the focus of other instruments of the 1.8m telescope (Aqueye+) or to the Nasmyth focus of the 1.2m telescope (Iqueye). This soft-mount-solution has the adavantage to facilitate the mounting of the photon counters, to keep them under controlled temperature and humidity conditions (reducing potential systematics related to varying ambient conditions), and to mitigate scheduling requirements. Here we will describe the first successful implementation of the Asiago intensity interferometer and future plans for improving it.

9907-23, Session 9

HBT SII imaging studies at the University of Utah

David B. Kieda, Nolan Matthews, The Univ. of Utah (United States)

This talk will describe the development of a fully digital implementation of the Hanbury-Brown-Twiss (HBT) intensity interferometry technique. This implementation uses a high-speed (250 Mhz) streaming digitizer to continuously record the light intensity observed by fast light sensors (photomultipliers, APDs, SiPM) at the focus of large (3-10 m) diameter Imaging Air Cherenkov Telescopes (IACTs). The digitized waveforms are sent to a high-speed computational facility to perform post-observation multi-telescope correlations. This strategy increases the scale and complexity of interferometry combinations that can be measured with a km-scale distributed array of 10-100 IACT telescopes, such as the future Cherenkov Telescope Observatory (CTA).

The talk will include recent progress made in image reconstruction of laboratory-simulated stars using pseudo-random light sources, and in reconstruction of source characteristics from these tests. The lecture will also describe SII observations performed using a pair of twin 3-m diameter optical telescopes, located at StarBase Utah, for the measurement of stellar diameters of several nearby stars. The talk includes a description of plans for testing SII capabilities at the VERITAS observatory in concert with the construction of the 9.6 m diameter Schwartzchild Couder telescope prototype, an ideal SII and IACT telescope for CTA.

9907-24, Session 9

Measurement of intensity correlations from laboratory and astronomical sources with single photon avalanche photodiodes and superconducting nanowire single photon detectors

Edward Schroeder, Philip Mauskopf, Nathan D. Smith, Genady Pilyavsky, Adrian Sinclair, Hamdi Mani, Arizona State Univ. (United States); Dmitry V. Morozov, Cardiff Univ. (United Kingdom); Karl K. Berggren, Di Zhu, Massachusetts Institute of Technology (United States)

We describe a detector module containing superconducting nanowire single photon detectors (SNSPDs) to be used for intensity interferometry to measure the angular diameters of stars. The SNSPDs are mounted in a small, easily transportable, cryostat coupled to single mode fiber optic cables through a hermetic feed-through. The detectors are read out with multistage microwave amplification and FPGA-based coincidence electronics. We successfully coupled these detectors to the Bok 2.3-m telescope on Kitt Peak and were able to obtain a count rate of 1 MHz for photons with a wavelength of 1.5 microns with a 12 nm bandwidth through

a single mode fiber from Capella, a 0.08 apparent magnitude star. This corresponds to an overall system efficiency of approximately 0.2%. The efficiency of coupling the single mode fiber to the telescope was primarily limited by the effects of atmospheric seeing which spreads the incident light from the star over approximately 100 modes in the focal plane. We will present progress on measurements with these detectors of correlations from two incoherent sources: a gas-discharge lamp with a laboratory set-up and a star with a rooftop set-up. The use of superconducting photon counting detectors for interferometry has a number of potential advantages over traditional Michelson interferometry and over the original set-up of Hanbury Brown and Twiss for intensity interferometry. The high time resolution of the SNSPDs enables measurements of diameters of bright stars with relatively small telescopes (~30 cm) that can have high efficiency for coupling to a single mode fiber even in the presence of atmospheric turbulence. In the future, the diameters of highly luminous, compact objects such as white dwarfs and black hole accretion disks may be measured with SNSPDs or other single photon detectors on larger telescopes with adaptive optics to provide high coupling efficiencies and baselines on the order of kilometers. This is not achievable through conventional methods of amplitude interferometry that rely on physical beam interference.

9907-25, Session 10

The orbit of the mercury-manganese binary 41 Eridani

Christian Hummel, Markus Schöller, European Southern Observatory (Germany); Gilles Duvert, Institut de Planétologie et d'Astrophysique de Grenoble (France) and Univ. Grenoble Alpes (France); Jean-Baptiste Le Bouquin, Institut de Planétologie et d'Astrophysique de Grenoble (France) and Univ. Joseph Fourier (France); Swetlana R. Hubrig, Leibniz Institute for Astrophysics Potsdam (Germany)

The mercury-manganese (HgMn) stars are a class of peculiar main-sequence late-type B stars. Their members show a wide variety of abundance anomalies with both depletions (e.g., He) and enhancements (Hg, Mn) and tend to be slow rotators relative to their normal analogs. These stars form a sub-class of the chemically peculiar (CP) stars. The chemical alterations are thought to be due to diffusion in quiet stellar atmospheres. More than two thirds of the HgMn stars are known to belong to spectroscopic binaries (Hubrig & Mathys 1995) with a preference of orbital periods ranging from 3 to 20 days.

Interferometric orbits were already measured for Phi Herculis (Zavala et al. 2007), Chi Lupi (Le Bouquin et al. 2013), and Alpha Andromedae (Pan et al. 1992). Here we report on a program to study the binarity of HgMn stars with the PIONIER near-infrared interferometer at the VLTI on Cerro Paranal, Chile. Among some 30 stars, companions were found for 10 of them, and the data allowed the determination of the orbital elements of 41 Eridani, with a period of just 5 days and a semi-major axis of under 2 mas.

Including the radial velocity measurements published by Hubrig et al. (2012), we derived masses of 3.10 +/- 0.06 times solar for each of the almost identical B9V stars (magnitude difference measured less than 0.1 mag). The orbital parallax is 18.14 +/- 0.16 mas, in good agreement with the Hipparcos trigonometric parallax of 18.33 +/- 0.15 mas. The stellar diameters are resolved as well at 0.38 +/- 0.03 mas. Using the sedFit tool (A. Boden, G. van Belle, priv. comm.) to estimate the bolometric flux, we derived an effective temperature of 10700 K for each of the stars, as well as diameters of 0.39 mas, in agreement with the measurements.

With other measurements of binary orbits in CP stars including Sigma Orionis A (Schaefer 2013), Lambda Virginis (Zhao et al. 2007), and Beta Arietis (Pan et al. 1990), allowing to derive stellar masses and luminosities, optical interferometry has provided important contributions to the understanding of CP stars in general.

9907-26, Session 11

IR-interferometric observations of AGNs: a diversity of dusty tori *(Invited Paper)*

Leonard Burtscher, Max-Planck-Institut für extraterrestrische Physik (Germany)

Interferometric observations in the infrared have resolved dusty structures on parsec and sub-parsec scales in more than two dozen AGNs by now -- a giant leap when considering that the first infrared interferometric observation of an extragalactic object is only 13 years old. Since then, studies have confirmed the existence of dust in AGNs at its sublimation radius and have clearly dismissed models of very extended tori. A few very well studied sources have been instrumental to reveal that the parsec-scale dust is distributed in multiple distinct components. It has come as a surprise for nearly everyone that the largest and brightest of these substructures is elongated in polar direction. Statistical studies have shown a perplexing diversity in the population as a whole. Surprisingly, the size-luminosity relation does not show the expected bimodality between optical type 1 and type 2 AGNs -- which are thought to arise from face-on and edge-on tori, respectively. This central premise of viewing-angle dependent unified models is challenged if not dismissed by interferometric observations.

9907-27, Session 12

The path to interferometry in space *(Invited Paper)*

Stephen A. Rinehart, NASA Goddard Space Flight Ctr. (United States)

For over two decades, astronomers have considered the possibilities for interferometry in space. The first of these missions was the Space Interferometry Mission (SIM), but that was followed by missions for studying exoplanets (e.g Terrestrial Planet Finder, Darwin), and then far-infrared interferometers (e.g. the Space Infrared Interferometric Telescope, the Far-Infrared Interferometer). Unfortunately, following the cancellation of SIM, the future for space-based interferometry has been in doubt, and the interferometric community needs to reevaluate the path forward. While interferometers have strong potential for scientific discovery, there are technological developments still needed, and continued maturation of techniques is important for advocacy to the broader astronomical community. We review the status of several concepts for space-based interferometry, and look for possible synergies between missions oriented towards different science goals.

9907-28, Session 12

Balloon experimental twin telescope for infrared interferometry: delay lines and optical alignment

Arnab Dhabal, Univ. of Maryland, College Park (United States); Stephen A. Rinehart, NASA Goddard Space Flight Ctr. (United States); Maxime Rizzo, Univ. of Maryland, College Park (United States); John E. Mentzell, Todd Veach, Dale Fixsen, Robert F. Silverberg, NASA Goddard Space Flight Ctr. (United States)

We present updates on the optics of Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII) as it gets ready for launch. BETTII is an 8-meter baseline far-infrared (30-90 microns) interferometer mission with capabilities of spatially resolved spectroscopy aimed at studying

star formation and galaxy evolution. The instrument collects light from its two arms, makes them interfere, divides them into two science channels (30-50 um and 60-90 um), and focuses them onto the detectors. It also separates out the NIR light (1-2.5 um) and uses it for tip-tilt corrections of the telescope pointing.

Currently, we have almost all the optical elements that have been heat treated, coated appropriately and are ready for use. We are presenting the procedure of mounting and aligning them using a LUPI interferometer. We also discuss the development of our inductive grid dichroic for separating the FIR from the NIR.

The warm and cold delay lines are an important part of this optics train. The warm delay line corrects for path length differences between the left and the right arm due to balloon pendulation, while the cold delay line is aimed at introducing a systematic path length difference, thereby generating our interferograms from where we can derive information about the spectra. The details of their design and the results of the testing of these opto-mechanical parts are discussed.

We also present results of interferometric simulations performed in FRED software to ascertain sensitivities of different optical elements on the interferograms produced. The limits of tip-tilt corrections on the external optics alignment errors have been taken into account in this analysis.

9907-29, Session 12

Recent experiments conducted with the Wide-field Imaging Interferometry Test bed (WIIT)

David T. Leisawitz, Roser Juanola-Parramon, Matthew R. Bolcar, NASA Goddard Space Flight Ctr. (United States); James R. Fienup, Alexander S. Iacchetta, Univ. of Rochester (United States); Stephen F. Maher, Science Systems and Applications, Inc. (United States) and NASA Goddard Space Flight Ctr. (United States); Stephen A. Rinehart, NASA Goddard Space Flight Ctr. (United States)

The Wide-field Imaging Interferometry Testbed (WIIT) was developed at NASA's Goddard Space Flight Center to demonstrate and explore the practical limitations inherent in wide field-of-view "double Fourier" (spatio-spectral) interferometry. The testbed delivers high-quality interferometric data and is capable of observing spatially and spectrally complex hyperspectral test scenes. Although WIIT operates at visible wavelengths, by design it delivers data that are representative of those from a space-based far-infrared observatory. WIIT was recently used to observe a calibrated, independently characterized test scene of modest spatial and spectral complexity, and an astronomically realistic test scene of much greater spatial and spectral complexity. In this presentation we will describe the experimental setup and the data acquired, along with an assessment of the performance of the testbed and a comparison of the data with analytical results.

9907-30, Session 13

The innermost astronomical unit of protoplanetary disks *(Invited Paper)*

Myriam Benisty, Jacques Kluska, Institut de Planétologie et d'Astrophysique de Grenoble (France)

Circumstellar disks around young stars are the birthsites of planets. It is thus fundamental to study the disks in which they form, their structure and the physical conditions therein. Of particular interest is the first astronomical unit in which terrestrial-planets form, and angular momentum is controled via mass-loss through winds/jets. With its milli-arcsecond resolution, optical interferometry is the only technics able to spatially resolve the first few AUs of the disk. In this review, I will present a broad overview of studies of young stellar objects with interferometry, and discuss prospects for the future.

9907-31, Session 14

Progress in polychromatic interferometry *(Invited Paper)*

Michel Tallon, Ctr. de Recherche Astrophysique de Lyon (France); Jacques Kluska, Univ. of Exeter (United Kingdom); Anthony Schutz, Lab. J.L. Lagrange (France) and Ctr. de Recherche Astrophysique de Lyon (France); Férréol Soulez, Ecole Polytechnique Fédérale de Lausanne (Switzerland); André Ferrari, Lab. J.L. Lagrange (France); Éric M. Thiébaut, Ctr. de Recherche Astronomique de Lyon (France); Bernard Lazareff, Fabien Malbet, Institut de Planétologie et d'Astrophysique de Grenoble (France); Isabelle Tallon-Bosc, Ctr. de Recherche Astronomique de Lyon (France); Gilles Duvert, Institut de Planétologie et d'Astrophysique de Grenoble (France)

By combining the light from several telescopes, Optical Interferometry provides the highest angular resolution (milliarcsecond resolution) in many fields such as stellar physics, star and planet formation, and environment of extra galactic black holes. In such fields, adding chromatic information allows insights in the physics and the dynamics of the observed objects. Besides astrophysical needs, a limited spectral bandwidth is also necessary for instrumental reasons like a larger coherence length or field of view. Thus considering collected light, instrumental performance also pushes toward a chromatic diversity of the interferometric measurements, making spectro-differential measurements accessible as well. This is why most of the current and future instruments provide a rich multi-spectral information.

Conversely, the availability of polychromatic data allows various improvements in processing interferometric data. Examples can be found in processing raw dispersed fringes, cophasing, image reconstruction, or model fitting.

The presentation will overview the ongoing work on Polychromatic Interferometry. In particular, it will draw on the results obtained by the POLCA project that combined experts in signal processing and Optical Interferometry to find out new methods to jointly process spatial and spectral information, and to improve both the performances (limiting magnitude, precision) and the observational capabilities (physics of the objects).

Particularly, evolving from monochromatic to polychromatic image reconstruction is challenging. Algorithms like SPARCO or the Self-Calibration Method combine monochromatic reconstruction in a smart way, but new approaches relying on the latest achievements in signal processing like alternating direction method of multipliers (ADMM) may open the way to an efficient global spatio-spectral reconstruction. MiRA-3D and PAINTER are on this track, allowing various spatio-spectral regularizations and constraints, including sparse approaches. Further, an optimal way to globally merge interferometric data with different chosen spectral resolutions is welcome to yet increase the performances of future large arrays.

Besides the expected efficient multi-spectral image reconstructors, optimal processing of dispersed fringes can improve fringe detection and cophasing, or even yield new unbiased observables or observables with a much better statistical distribution, yielding more accurate measurements.

Spreading the benefits of polychromatic processing will be made easier with the new version of the OIFITS standard format for interferometric data that now conveys spectral information like spectra, spectro-differential measurements, or spectral noise correlations.

9907-32, Session 14

Making high-accuracy null depth measurements for the LBTI exozodi survey

Bertrand P. Mennesson, Jet Propulsion Lab. (United States); Denis Defrère, The Univ. of Arizona (United States); Mathias Nowak, Observatoire de Paris à Meudon (France); Philip M. Hinz, The Univ. of Arizona (United States); Rafael Millan-Gabet, NASA Exoplanet Science Institute (United States) and Infrared Processing and Analysis Ctr. (United States); Olivier Absil, Lindsay Marion, Univ. de Liège (Belgium); Eugene Serabyn, Jet Propulsion Lab. (United States); William C. Danchi, NASA Goddard Space Flight Ctr. (United States)

The NASA sponsored LBTI-HOSTS mid-infrared survey aims at measuring the exozodiacal dust emission level of nearby main sequence stars down to an accuracy level (1?) of the order of 10 times the solar zodi level per star, and 2 zodis or less (1?) for the median emission level of the sample. To this end, extremely accurate null depth measurements must be made, typically down to the 500 ppm uncertainty level or less (1?) per star, roughly an order of magnitude better than previous state-of-the-art mid-infrared interferometry. We present here the data reduction method developed specifically for this task, together with commissioning and science grade measurements demonstrating a final on-sky calibrated null depth accuracy of 500 ppm or better around a wavelength of 11 microns. The reduction approach is based on the "null self-calibration technique" that we developed earlier in the context of single-mode infrared interferometry and showed significant improvements over classical reductions techniques. We discuss in this paper how we have further improved the technique to account for high-frequency path length fluctuations and the specifics of mid-infrared nulling observations at LBTI.

9907-33, Session 14

Data reduction of the VLTI/GRAVITY interferometric instrument

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The new VLTI/GRAVITY instrument is a four telescope beam combiner installed at the VLT Interferometer. The principal novelty of this instrument is the availability of a dual field mode enabling narrow-angle relative astrometry at 10 micro-arcsecond accuracy between two objects separated by several arcseconds. The fringe tracker (FT) stabilizes the interference fringes at up to 1 kHz frequency, allowing for long exposures with the science combiner (SC) as well as phase referenced imaging and differential astrometry (in dual field mode). The FT and SC beam combiners are integrated optics (IO) components, whose 24 outputs are (optionally) polarization-split and spectrally dispersed. The processing of the photometric signals from the IO components is based on the pixel-to-visibility matrix (P2VM) formalism, that translates them into complex visibilities. The retrieval of the relative phase of the two objects subsequently relies on the combination of the phases measured from the FT, SC and the laser metrology. We will present the adopted algorithms, and an overview of the structure of the developed software. The calibration of the wavelength scales of the FT and SC at the required accuracy presents specific difficulties that we will briefly discuss. Preliminary examples of the reduction of on-sky data obtained during the commissioning will also be presented.

9907-34, Session 15

The second version of the OIFITS data exchange format for optical/IR interferometry *(Invited Paper)*

Gilles Duvert, Institut de Planétologie et d'Astrophysique de Grenoble (France) and Univ. Grenoble Alpes (France); John S. Young, Univ. of Cambridge (United Kingdom); Christian Hummel, European Southern Observatory (Germany)

We present the second version of the OI Exchange Format (OIFITS2), the standard for exchanging calibrated data from optical (visible/infrared) interferometers. This new version provides definitions of several new tables addressing the needs of future interferometric instruments such as GRAVITY and MATISSE. Also included are optional data columns for a more rigorous description of measurement errors and their correlations. It also introduces many new header keywords allowing more effective data discovery by providing useful metadata. OIFITS2 may also be considered as a new step towards the design of a common data model for optical interferometry. In this paper, we outline the new features of OIFITS2 and describe their anticipated usage. The ongoing community efforts to adopt OIFITS2 and stress-test it in the real world are also presented.

9907-35, Session 15

Aspro2: get ready to 2nd generation instruments (GRAVITY and MATISSE)

Laurent Bourgès, Observatoire des Sciences de l'Univers de Grenoble (France); Gilles Duvert, Institut de Planétologie et d'Astrophysique de Grenoble (France)

Aspro 2 is a complete observation preparation tool developed and maintained by the JMMC that allows to prepare interferometric observations with the VLTI or other interferometers (CHARA, SUSI, NPOI).

Available since 2010, it is regularly updated to provide new features (analytical and user models) and an up-to-date configuration corresponding to ESO & CHARA Call For Proposals.

As new instruments GRAVITY & MATISSE, the 2nd generation VLTI instruments, will be soon available to the community, Aspro 2 is evolving to support them:

The noise modeling has been improved for the future MATISSE instrument (L/M & N bands): thermal noise contribution and atmospheric transmission.

Moreover, the OIFITS simulation has been rewritten to generate correlated

quantities (VIS2, VIS, T3) and will support OIFITS-2 soon.

It is already supporting GRAVITY observations (commissioning) by providing a preliminary configuration and exporting Observing Blocks (P2PP).

9907-36, Session 15

Spectrally dispersed Fourier-phase analysis for redundant apertures

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It has now been demonstrated that well AO-corrected images produced by ground based telescopes can be used to produce interferometric observables robust against residual wavefront errors called kernel-phase which are a generalization of the more common notion of closure-phase. Since it preserves the full instrument throughput and leads to a potentially large number of observables, the kenel-phase analysis of conventional images is, given sufficient AO-correction, emerging to be a more satisfactory option than its sparse aperture masking counterpart.

It has also been shown, by the same token that, assuming this time some level of asymmetry in the pupil, information about the wavefront can also be extracted from images of a point source, this time relying on the complementary eigen-phase relations, provided by the linear phase transfer model at the heart of both kernel- and eigen-phase data analysis.

Because it relies on a linearization of the phase transfer equation, this model is intrinsically limited to a regime of aberration where the rms error is less than the wavelength. This paper describes a possible extension of the Fourier-phase analysis method, here applied to a set of spectrally dispersed data, similar to those produced by an intergral field spectrograph. In this dispersed case, the original residual aberration constraint is considerably relaxed as it now needs to be less than the coherence length. Given sufficient wavelength coverage, the phase-transfer model can be used to produce novel spectrally dispersed kernel-phase information on a target of interest, or be used for wavefront sensing purposes, for any aberration regime.

9907-37, Session 16

Enabling the direct detection of Earth-sized exoplanets with the LBTI HOSTS project: a progress report

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NASA has funded a project called the Hunt for Observable Signatures of Terrestrial Systems (HOSTS) to survey nearby solar type stars to determine the amount of warm zodiacal dust in their habitable zones. The goal is not only to determine the luminosity distribution function but also to know which individual stars have the least amount of zodiacal dust. It is important to have this information for future missions that directly image exoplanets as this dust is the main source of astrophysical noise for them. The HOSTS project utilizes the Large Binocular Telescope Interferometer (LBTI), which consists of two 8.4 m apertures separated by a 14.4-m baseline on Mt. Graham, Arizona. The LBTI operates in a nulling mode in the mid-infrared spectral window (8-13 microns), in which light from the two telescopes is coherently combined with a 180 degree phase shift between them, producing a dark fringe at the location of the target star. In doing so the starlight is greatly reduced, increasing the contrast, analogous to a coronagraph operating at shorter wavelengths. The LBTI is a unique instrument, having only three warm reflections before the starlight reaches cold mirrors, giving it the best photometric sensitivity of any interferometer operating in the mid-infrared. It also has a superb Adaptive Optics (AO) system giving it Strehl ratios greater than 98% at 10 microns. During the past year LBTI has been undergoing commissioning, and the HOSTS project team passed its Operational Readiness Review (ORR) in April, 2015. The team recently published papers on the target sample, modeling of the nulled disk images, and initial results such as the detection of warm dust around eta Corvi. Additional papers are in preparation on beta Leo and on the data pipeline. We will report recent progress, new results, and plans for the science verification phase that started in February 2016, and for the survey.

9907-60, Session PSWed

How to create space inside the VLTI: PIONIER 3D project

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PIONIER is a four beams combiner instrument developed by the Astrophysics Laboratory of Grenoble (LAOG). This instrument arrived at the ESO Paranal Interferometer in 2010 as a visitor instrument and was supposed to be decommissioned with the arrival of the second generation instruments GRAVITY and MATISSE. The success of PIONIER induced the needs to keep it available for the scientific community inside the already full environment of the VLTI. This paper presents the technical solutions that were applied to place the instrument in mezzanine without impact on the performance and with the constraint of reducing the workload in operation.

9907-61, Session PSWed

The intrinsic limitations of the VLTI Auxiliary Telescopes array

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The VLTI AT array is composed of 4 relocatable telescopes, a network of stations and 6 delay lines. This array is used in operations to offer various configurations covering a large range of u,v spatial frequencies. We present here the current configurations offered and the rationale and limitations behind the current offering. We present also some speculative reflections on how we could address these limitations in the future.

9907-62, Session PSWed

Fundamental gain in high-contrast imaging with the Large Binocular Telescope Interferometer

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Numerical simulations for the Large Binocular Telescope Interferometer have shown a fundamental gain in contrast when using two 8m adaptive optic telescopes instead of one in a high Strehl regime. The global gain is improved by a factor 2 in contrast by using the long exposures and by a factor of 10 in contrast by using the short exposures. Indeed, fringes are still present in the short exposure, contrary to the long exposure where the fringes are smoothed. Thus, there is some gain in grouping some short exposures with high gain G. This makes the LBTI well suitable for the Angular Differential Imaging technique. A planet will be alternatively located in the fringes (G ~ 10 to 100) and either in the dark rings (G ~ 4 to 20) or in the white rings (G ~ 1), depending on its radial distance. A rotation of 30° is sufficient to pass through at least one gain zone. The LBTI can provide in the visible wavelength not only high angular resolution (~ 6.5 mas at 750 nm) and high sensitivity (by a factor 4), but also a gain in contrast (by a factor 10 to 100) compared to the stand-alone adaptive optic used on each LBT aperture.

9907-63, Session PSWed

Sensitivity to differential piston and to adaptive optic errors with the Large Binocular Telescope Interferometer

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On-sky adaptive optic wavefront screens have been used and random optical path fluctuations have been included in numerical simulations for the Large Binocular Telescope Interferometer. We characterize the Point Spread Function (PSF) and the Optical Transfer Function (OTF) by computing respectively the Strehl and the interferometric visibility criteria. We study the contribution of the wavefront disturbance induced by each adaptive optic system and by the optical path difference (differential piston) between the arms of the LBTI. We study separately both effects. To provide an image of quality suitable with standard science cases, the requirements for a LBTI mode at the visible wavelength (750 nm) must be at least an adaptive optic wavefront RMS fluctuation below ?/32 ~ 25 nm, or a Strehl above 90% provided by each adaptive optic system, and a differential piston RMS fluctuation below ?/8 ~ 100nm in the overall LBTI system. The adaptive optic wavefront errors - mainly the differential tilt - appear to be more critical than the differential piston.

9907-64, Session PSWed

Performance of the MROI fast tip-tilt correction system

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The fast tip-tilt correction system for the Magdalena Ridge Observatory Interferometer (MROI) has been designed, manufactured and tested by the University of Cambridge. The system uses passive thermal compensation to maintain the stability of the tip-tilt reference direction over a 5 degree Celsius ambient temperature change, and an electron-multiplying CCD camera and optimised centroiding algorithm to reach faint limiting magnitudes. We present results from a programme of laboratory tests to validate the system performance. The experiments verifying the opto-mechanical stability comprised tests of the mounts supporting individual optics as well as end-to-end "integrated" tests of the entire system. We also report measurements of the closed-loop tilt correction performance in the presence of synthetic atmospheric tilt disturbances, as a function of the target brightness. In the best 0.7 arcscecond seeing, we find that the system operates reliably at a visual magnitude of 15.9 and delivers two-axis tilt residuals of 0.060 arcsec for a magnitude 14.0 target. On-sky tests of the system are planned for summer/fall 2016, following the commissioning of the first MROI Unit Telescope.

9907-65, Session PSWed

GRA4MAT: combining GRAVITY and MATISSE at the VLTI

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MATISSE is the 2nd generation interferometric instrument for the ESO VLTI, covering the L, M and N-bands. MATISSE does not have an internal fringe-tracker and will thus be limited to exposure times, which are shorter than the atmospheric coherence time. This obviously puts severe constraints on the achievable limiting magnitude and thus observable science objects with MATISSE in stand-alone mode. The approach to overcome these limitations is to use the fringe-tracker of another 2nd generation VLTI instrument, namely GRAVITY to measure the OPD fluctuations and the delay-lines of VLTI to correct them. In this paper we will give a motivation for this approach and the boundary conditions. Furthermore, the concept of the software architecture and the expected performances will be discussed.

9907-66, Session PSWed

SCSI: the Southern Connecticut Stellar Interferometer

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The technique of intensity interferometry, also known as the Hanbury-Brown and Twiss effect, has largely been neglected in astronomy since the late 1970's, mainly because it is inherently limited in terms of the signal-to-noise ratio, meaning that large telescopes were needed to collect enough light to observe even the brightest stars in the sky. Compared with amplitude-based interferometry, generally done with much smaller apertures and yet reaching considerably fainter magnitudes, there appeared to be little reason to pursue intensity interferometry after the success of the precursors to the current generation of amplitude-based interferometers was demonstrated. However, it is time to revisit this technique because commercially available electronics can time events with precision on the level of picoseconds and detector development has led to the pixel arrays with comparable precision in photon arrival times. This has the possibility to mitigate the sensitivity issue, as the signal-to-noise ratio in intensity interferometry is proportional to the square root of the detection bandwidth.

At Southern Connecticut State University (SCSU), we are building a stellar intensity interferometer based on single photon avalanche diode (SPAD) arrays. In this paper, we describe the instrument that is now under construction, which uses an 8-pixel SPAD array, and we present initial engineering data and performance estimates. The main use of the system will be on the campus of the university in New Haven, Connecticut, but we also plan to take the detectors and timing correlators to other observatories in order to use them with larger telescopes than we will have available on campus. By implementing SPAD arrays, it will be possible to conduct several independent intensity interferometry observations at the same time using the same pair of telescopes by putting light of a different wavelength on each pixel of the SPAD device. This is a key technology demonstration that, together with the SPAD detectors and fast electronics, could make the signal-to-noise ratio achievable with the technique more comparable to that of amplitude-based interferometers in the coming years. In addition, if the technique can be made wireless, then the maximum baseline could be significantly larger than current amplitude-based interferometers.

9907-67, Session PSWed

Monitoring a decade of seeing at the NPOI site with quad cell measurements

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As a part of regular operations, the NPOI uses Narrow Angle Trackers for atmospheric tip-tilt correction. This correction is done using a quad cell array for each siderostat, and is based on the error signals measured by these arrays. We compiled error signal information from these quad cells for the period between 2004 and 2015. This information is correlated with atmospheric coherence times measured using NPOI data and quasi simultaneous seeing measurements done with another telescope on Anderson Mesa. This combined dataset allowed us to convert the quad cell error information into atmosphere coherence length values. We will present details about this technique, and the calibration procedure. We will also present seeing statistics and the investigate the evolution of the atmospheric conditions of the NPOI site over the last decade.

9907-68, Session PSWed

Magdalena Ridge Interferometer: UT#1 site installation, alignment, and test

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The deployment of the Magdalena Ridge Optical Interferometer has resumed in 2015 thanks to additional funding from Air Force Research Laboratory spread over 5 years granted to New Mexico Tech (NMT).

In the first stage of the project, AMOS was awarded for the design and construction of the unit telescopes mounts to be installed on the optical array. The first telescope mount (UTM#1) has been delivered to NMT after successful completion of factory test in Belgium. The main parts for UTM#2 and UTM#3 have been manufactured and pre-assembled at AMOS.

The project restarts with the installation of UTM#1 on the Ridge and the site acceptance tests. These tests demonstrate the ability of the telescope to perform according to the somewhat uncommon requirements since the telescope are dedicated to interferometry.

The site activities occurs in three phases for which appropriated teams of technicians and engineers come on-site to complete their work: a.) the installation on the pier and mechanical integration, b.) the alignment of the optics and c.) the site acceptance test.

Thanks to the compactness of the elevation-over-elevation mount, the telescope is brought on the Ridge in one piece. Only the optics and their supports are transported in a separate crates. The telescope is installed on a concrete pier dedicated to the site acceptance and commissioning of the telescope.

The optical configuration is a Mersenne beam compressor. From the 1425 mm primary mirror to the 95 mm output collimated beam in line with the outer axis of the mount, the light hits only three surfaces: the primary and secondary rotating with the inner axis and the tertiary located at the pivot point, intersection of inner and outer axis and rotating half of the inner elevation angle.

The first task of the alignment consists of co-aligning the tertiary mirror rotating axis with the inner axis of the telescope. Then, the primary and secondary are aligned so that their optical axes are concurrent with the pivot point. This can be done efficiently by using a laser tracker and other metrology. The mechanical alignment is further validated and optimized by measuring the pupil stability in the entire field of regard of the telescope thanks to a long focal imaging lens.

The next step of alignment does not requires further mechanical alignments but only correction of the secondary mirror position using a motorized high-accuracy hexapod. The quality of alignment is evaluated using a built-in Shack Hartmann wavefront sensor. In addition to the baseline alignment of the optics, the hexapod provides the ability to compensate for the misalignment of the optics due to gravity and temperature changes. This correction can be performed either on the basis of the wavefront measurement feedback or on the basis of an open-loop correction law for simultaneous image quality and pupil stability optimization.

Once the telescope alignment is completed and the correction laws for pointing and M2 position are consistent, the final acceptance tests take place in order to assess the performance of the telescope and its ability to meet the stringent requirements for interferometry.

9907-69, Session PSWed

VLT Interferometer upgrade for the 2nd generation of interferometric instruments

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ESO is undertaking a large upgrade of the infrastructure on Cerro Paranal

in order to integrate the 2nd generation of interferometric instruments Gravity and MATISSE but also to increase its performance. This upgrade has started at the beginning of March 2015 and will end with the implementation of the adaptive optics system for the Auxiliary telescope (NAOMI) in 2018. This upgrade has an impact on the infrastructure of the VLTI as well as its systems and scientific instruments.

MIDI has been decommissioned. PIONIER has been moved to a new position inside the VLTI laboratory. The power, cooling and network capabilities have been increased in the VLTI laboratory but also in the basement of the UTs and in the Combined Coude Laboratory for the instrument ESPRESSO. A new maintenance station for the Auxiliary telescope (AT) has been opened on the VLTI platform. The star separators in the ATs and Unit Telescope (UTs) have been commissioned and delivered to science operation. The Gravity beam combiner has been integrated and is under commissioning as well as its metrology system. The Infrared Adaptive optics system is being implemented in the Coude of the UTs. The visible adaptive optics system which are already in use since 2003 has been upgraded.

The Coude train of the ATs will be replaced to gain a better transmission at the end of 2016 and beginning 2017. MATISSE will be delivered to Paranal at the end of 2017 and it will use Gravity as fringe tracker to increase its performance. Finally in 2018 NAOMI will be delivered and commissioned.

We give here a description of this global upgrade and also the expected performances.

9907-70, Session PSWed

NAOMI: a low-order adaptive optics system for the VLT Interferometer dual-feed light beams

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The New Adaptive Optics Module for Interferometry (NAOMI) will be developed for and installed at the 1.8-metre Auxiliary Telescopes (ATs). The four ATs are designed for interferometry applications. Currently the ATs are equipped with a visible tip/tilt sensor called STRAP (System for Tip/tilt Removal with Avalanche Photodiodes) and the corrections are applied with a fast steering mirror. Under good seeing conditions this provides a reasonable correction of the atmospheric turbulence in the K and N -bands, but as soon as the seeing degrades below 1 arcsecond, the instantaneous Strehl ratio delivered by the telescopes degrades significantly. The goal of the project is to equip all four ATs with a low-order Shack–Hartmann adaptive optics system operating in the visible, in place of the current STRAP, in order to overcome the current limitations.

By improving the wavefront quality delivered by the ATs for guide stars brighter than R = 13 mag, NAOMI will make the existing interferometer performance less dependent on the seeing conditions. The quality of interferometric data will therefore improve as a result. Fed with better and more stable image quality, the fringe trackers will achieve the fringe stability necessary to reach the full performance of the second generation instruments GRAVITY and MATISSE.

NAOMI has passed its preliminary design review in 2015 and the first system is planned to be installed in 2018. ESO has teamed up with the Institut de Planétologie et d'Astrophysique de Grenoble by the end of 2015 to strengthen the project team for the development of the corrective optics unit and production of the full systems.

9907-71, Session PSWed

On sky effects of synchronizing the real-time computers of the GRAVITY fringe tracker

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Gravity fringe tracker is able to stabilize the K-band fringes on six baselines at the same time. I has been designed to achieve a performance for average seeing conditions of a residual OPD lower than 300 nm with objects brighter than K = 10. The control loop of the tracker is composed of a three stage real time system compromising: a sensor where the detector pixels are read in and the OPD and GD are calculated; a controller receiving the computed sensor quantities and producing commands for the piezo actuators and a third stage where current measurements are monitored in real time and used to update the control parameters based on a Kalman estimation. The hardware and software implementation of this design compromises three independent real time computers (one per stage) running asynchronously and communicating data via the Reflective Memory Network. With the purpose of improving the performance of the GRAVITY fringe tracking control loop, a deviation from the standard asynchronous communication mechanism has been proposed and implemented. This new scheme operates the three real time computers involved in the tracking loop synchronously using the Reflective Memory Interrupts as coordination signal. This has the desired effect of reducing the total pure delay of the loop from 4 [ms] to 2.5 [ms] which then translates on a better stabilization of the fringes as the bandwidth is substantially improved. This paper will explain in detail the real time architecture of the system in its synchronous implementation. Using commissioning data, the improvements will be quantified in detail. Finally, a path for a further reduction of the pure delay will be described including the expected gains in terms of bandwidth and residual OPD for the nominal observation case.

9907-73, Session PSWed

The metrology system of the VLTI instrument GRAVITY

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The VLTI instrument GRAVITY combines the beams from four telescopes interferometrically and provides high-resolution phase-referenced imaging as well as narrow-angle astrometry together with spectroscopic and polarimetric capabilities. For this purpose, the beam combiner observes two celestial objects simultaneously in dual-field mode in order to extract the differential optical path difference (dOPD) resulting from their angular separation on sky. This measurement is provided by the metrology system of GRAVITY, which traces and subtracts the internal dOPDs within the interferometer from the detected ones between the targets to obtain their actual dOPD on sky.

Here, we present the general overview of this novel metrology system. We developed a three-beam laser system injected via fiber optics to the beam-combiner instrument of GRAVITY and a homodyne detection scheme for three-beam interference using phase-shifting interferometry in combination with lock-in amplifiers. The technical details of the three-beam and homodyne detection concept will be described in the contribution of Blind et al. (AS104-159).

In this way, backscattering of the metrology light onto the science detector is minimized as well as non-common path effects caused by temperature fluctuations from variations of high-power laser radiation. In addition, the metrology traces all the optical paths from the beam combination of the astronomical light back to the telescopes. Since there the dOPD measurements are performed in the pupil planes, the definition of astrometric baselines is essentially free of systematics. Via this approach the metrology system measures dOPDs on a nanometer-level corresponding to precision astrometry of order 10μas.

9907-74, Session PSWed

Data reduction for the MATISSE instrument

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We will present the data reduction software of the MATISSE instrument. It combines several neat features seen in previous pipelines to make the most out of the MATISSE data, and includes brand new features that will make MATISSE an imaging instrument. It will estimate the optical path difference (OPD), will process the OPD modulation of the instrument as it was done in the MIDI instrument, it will correct for photometric imbalance as is done in the FLUOR and AMBER instruments, and will calibrate the observations the same way as it is done in AMBER. On the other hand, the MATISSE pipeline will provide the IRBIS software, which makes available image reconstruction to the end user. The whole software is packaged to be used together with the flexible Reflex environment developed by ESO to make available instruments pipelines to the end user. These features make the MATISSE software unique.

9907-75, Session PSWed

ALOHA/CHARA at 1.55 μm: sensitivity improvement and on-sky ability to detect astronomical sources in H band

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Our research team has developed an innovative fibre stellar interferometer using properties of nonlinear optics. This concept named ALOHA (Astronomical Light Optical Hybrid Analysis) offers an alternative for high resolution imaging at very low flux level in the mid-infrared wavelength domain (3-20 μm range) where the required devices are not yet available or currently have poor performance. Thanks to a sum frequency generation (SFG) process achieved in a nonlinear crystal on each arm of the interferometer, the light is shifted to the visible or the near-infrared domain and then processed by available components (optical fibres, guided components, detectors...) from the telecommunications domain. The current laboratory setup is a prototype of interferometer with two arms using periodically poled Lithium Niobate (PPLN) waveguides powered by a 1.06-μm laser pump source to convert a signal at 1.55 μm to 630 nm. The upconversion process is only efficient on a 0.6-nm window centred at 1.55 μm. The coherent recombination of the two arms is achieved through guided optics components in the visible domain. The performance of the overall interferometric instrument is reliant on the quality of the hybrid process in terms of PPLN waveguide conversion efficiency and additional noise control.

To validate our proposal for high resolution imaging, the prototype is tested on-sky thanks to collaboration with the CHARA team. A preliminary mission in May 2014 has allowed to validate the on-site implementation of the SFG process and to lead a sensitivity test in H band with a single arm of the interferometer to predict the performance of the complete instrument in its interferometric configuration. With the atmospheric conditions during the observing run, a 2.2 magnitude star has been detected with a signal-to-noise ratio (SNR) of 3 for an integration time of 15 min and only observing 0.6 nm of the object spectral bandwidth. In summary, thanks to this photometric calibration combined with a numerical simulation and laboratory tests on the prototype, we can predict the sensitivity of the interferometer within specific conditions. Thus we have determined that with a seeing radius of 6 cm (typical value in April-May at CHARA) and a measured contrast of 70 % with a 34-m baseline, an astronomical object of Hmag = 2 can be detected over an integration time of 16 minutes. Currently the main goal is to achieve the first fringes on-sky with ALOHA at 1.55 μm.

Furthermore the next step involves extending the concept to a wide-band analysis. We therefore propose to use a frequency comb as a pump source to sample the broadband spectrum and to enlarge the analysed spectral bandwidth by simultaneous SFG process in the nonlinear waveguide. A first laboratory experiment was performed in high flux regime with only a dual-line pump to investigate the spectral filtering effect on the temporal coherence behaviour. We demonstrated a modification of the temporal coherence properties of the converted wave due to a spectral compression effect that only acts on the gap between the spectral samples.

9907-76, Session PSWed

The new classic instrument for the Navy Precision Optical Interferometer

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The New Classic instrument was built as an electronics and computer upgrade to the existing Classic beam combiner at the Navy Precision Optical Interferometer (NPOI). The classic beam combiner is able to record 32 of 96 available channels and has a data throughput limitation which results in a low duty cycle. Additionally the computing power of the Classic system limited the amount of fringe tracking that was possible. The New Classic system implements a high-throughput data acquisition system which is capable of recording all 96 channels continuously. It also has a modern high-speed computer for data management and data processing. The computer is sufficiently powerful to implement more sophisticated fringe-tracking algorithms than the Classic system, including multi-baseline bootstrapping. In this paper we described the New Classic hardware and software, including the fringe-tracking algorithm, performance, and the user interface.

9907-77, Session PSWed

A triple modulation to optimize the accuracy of the VLTI instrument MATISSE

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MATISSE is the 4 beams 2nd generation VLTI instrument. It will work in the middle infrared in the L, M and N bands at several spectral resolutions ranging from Low (30) to High (5500 in L). The observations in L-M and N will be simultaneous, as the light is send in two different cryostats, each with its own spectrograph and detector. In N band the dominant noise results from the variations of the thermal background, that are 10e4 to 1e05 times more important than the second source of noise that is the background photon noise. In optical interferometry, these background variations result in variations of the intensity of the low frequency peak (LFP). Therefore, the low frequency peak must be reduced by more than 10e5 at the frequencies of the first fringe peak. The first modulation, which is the built-in spatial modulation introduced by an all-in-one multi-axial beam combiner, reduces the LFP down to a few percent below the first fringe peak. Using a Hanning filter on the interferometric window can reduce this to a few 10e-4 but with a cost of about 2 in equivalent transmission. In MATISSE, an additional attenuation is obtained by a temporal modulation of the fringes. As we have anyway to record about 10 frames in a coherence time, to avoid detector saturation, we introduce an OPD step of about lambda/10 before each new frame. Then the fringe signals are demodulated before being coherently added within the coherence time, but the demodulation of each fringe peaks modulates the LFP (and the other fringe peaks) and reduces its average well below 10e-5 even with a very reduced Hanning filtering. This combination of spatial and temporal modulation has two other advantages. First it also reduces the crosstalk between fringe peaks at different baselines well below 10e-5, which is necessary to expect the 0.1 milliradian closure phase accuracy needed for the most extreme high contrast goals of MATISSE that are the direct detection of exoplanets. Second, it can also be applied in L band, where it is not possible to make a modulation cycle in the coherence time, but even with one step per coherence time, the modulation introduced on the LFP and other fringe peaks reduces the systematic effects in the instrumental phase. The last modulation present is the Beam Commutation Device that switches beams (1 <-> 2) and (3 <-> 4) at the end of each exposure, typically every minute. Such a beam commutation changes the sign of the source closure phase and differential phase without modifying the instrument systematic and slowly variable contributions to these measures. Then the combination ("BCD+" - "BCD-") eliminates these instrument contributions without SNR cost. This is a decisive feature to obtain the high accuracy wavelength dependent closure and differential phases necessary for high contrast polychromatic imaging and model fitting over the full 3 to 13 microns MATISSE spectral coverage.

9907-78, Session PSWed

GRAVITY acquisition camera software: characterization results

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GRAVITY acquisition camera implements four optical functions to track multiple beams of Very Large Interferometer (VLTI): a) pupil tracker: images four pupil reference lasers mounted on the spiders of each telescope M2 using a 2 x 2 lenslet; b) field tracker: images science stars; c) pupil imager: reimages telescopes pupil; d) aberration tracker: implements four Shack-Hartmann images. The estimation of beam stabilization parameters from the acquisition camera detector image is carried out, for every 1 s, with a dedicated data reduction software. It measures the pupil shifts (lateral and longitudinal), field tip-tilts and beams higher order aberrations of four telescopes of the VLTI.

The development of acquisition camera data reduction software is challenging due to the involvement of complex imaging system, field rotations and the software is required to work for all four telescopes simultaneously in the closed loop.

The field tracker software evaluates brightest star's position in the 4 x 4 field of view. It is implemented in two steps. In the first step, stars in the field are scanned using a predetermined star FWHM as a threshold. In the second setp, the detected stars are sorted out on the flux order. A Gaussian fit is applied to the brightest star to obtain its accurate position.

The determined star position is used in stabilizing the star light injection into single mode fibers, which carry the telescope beams to the coherent beam combination. The acquisition camera works in the H-band and the science beam combination is implemented in the K-band. The position error caused by the atmospheric dispersion between the H and K-bands is measured and corrected. Stars with different spectral types will have different amounts of atmospheric dispersion. Therefore, in these calculations, the color of the star is taken into account.

The pupil tracker evaluates lateral and longitudinal pupil positions for each telescope. As a first step in the software, positions of the pupil tracker spots (2 x 2 lenslet images of four pupil reference laser beams) are computed using a predetermined spot FWHM as a threshold. Secondly, these spot positions are compared with the reference grid to calculate the spot shifts. Spot shifts in x and y directions allow one to measure the lateral pupil positions. The amount of divergence or convergence of spot shifts allows one to evaluate the longitudinal pupil positions.

The aberration sensor measures quasi-static aberrations of beam in the Zernike polynomials. As a first step in the software, Shack-Hartmann spot positions are computed using standard algorithms: a) for a point source, a weighted centroid algorithm is used; b) for an extended scene, a correlation algorithm is used. Secondly, by comparing the spot positions with the reference grid, wavefront slopes and thereby corresponding Zernike polynomials coefficients are evaluated.

The measured parameters are updated in the instrument online database. These parameters are used in: a) alignment of GRAVITY with the VLTI; b) active pupil and field stabilization; c) the wavefront aberrations are currently being used for defocus correction and for an engineering purpose. The pupil imager is used to monitor the pupil visually during the observations.

The acquisition camera software is now successfully operational on-sky in closed loop. The software is characterized with the experimentally simulated stars using GRAVITY calibration unit and also on-sky during GRAVITY installation and verification phase at Paranal. The characterization performance results show that the acquisition camera beam sensing accuracies are within GRAVITY specifications.

The relevant data reduction, the calibration procedures and their characterization results are reported.

9907-79, Session PSWed

MATISSE: specifications and expected performances

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MATISSE is the next generation spectro-interferometer at the European Southern Observatory VLTI operating in the spectral bands L, M and N, and combining four beams from the unit and auxiliary telescopes. The instrument will be entering its testing phase early 2016. This paper presents the equations describing the MATISSE signal and the associated sources of noise. The specifications and the expected performances of the instrument are then evaluated taking into account the current characteristics of the instrument and the VLTI infrastructure, including transmission and contrast degradation budgets. We present as well the MATISSE simulation tools that will be made available to the future users.

9907-80, Session PSWed

GRAVITY: the new metrology concept

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GRAVITY is a dual-feed four-telescope K-band combiner for the VLTI, aiming at precision narrow-angle astrometry and phase-referenced interferometric imaging. To this end, a metrology system traces the differential optical path difference (dOPD) between the science and the reference targets, inside the GRAVITY BCI and the VLTI infrastructure, backward from the spectrometers to the telescopes spiders. The metrology receivers placed there measure temporally modulated fringes between the two beams, from which the metrology dOPD is estimated. Subtracting these measurements from the stellar fringe phases of both targets determines their astrometric distance on sky.

During the integration at MPE, it was discovered that GRAVITY suffers from an extremely strong Raman and fluorescence back-scattering from the 20-m fluoride fibers, excited by the metrology laser. Stellar fringes were then contaminated on the spectrometers detectors by a strong incoherent light background, dramatically reducing the instrument sensitivity by more than 10 stellar magnitudes.

Hence a new metrology scheme has been developed to mitigate this issue. We present here in details this new concept, based on two innovative solutions: a three-beam metrology concept and the heavy use of lock-in amplifiers. The addition of a third, bright (>50mW) metrology beam allows decreasing the laser power in fibers by a factor of 100-1000, decreasing proportionally the back-scattering as well as non-common path thermal effects, while preserving the signal-to-noise ratio. But performance is ultimately limited by laser power fluctuations. Lock-in amplifiers (LIAs) are then used to demodulate the metrology fringe signal. They act as narrowband bandpass filters (bandwidth ~ 100 Hz) for any freely selectable modulation frequency up to ~15 kHz. Hence, they efficiently filter out the three-beam laser power fluctuations, as well as vibrations in the system. This new concept proved to mitigate the back-scattering effect to a level where GRAVITY can operate again with optimal performance

Note that the present contribution focuses on a detailed description of this new metrology concept. Its implementation in GRAVITY as well as the overview of the metrology system is presented in another contribution from our team (Lippa et al., AS104-58).

9907-81, Session PSWed

Co-phasing progress of a Fizeau interferometry telescope

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Fizeau interferometer produces direct image from a combined primary mirror, and a wide field of view. It's very useful in high resolution astronomical imaging. We have studied Fizeau optical interferometry, and carried out some experiments. A sparse aperture interferometry system is established, the primary mirror constitutes of several parabolic mirror (sub-aperture is 150mm). We have achieved a preliminary co?phasing deviation of 1?m, by means of a FISBA interferometer. Then, dispersed Rayleigh interferometry method is used for more precise measurement.

9907-82, Session PSWed

Robust control for fringe tracking in optical interferometry

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Fringe tracking (FT) is a critical component of an Optical Long Baseline Interferometer (OLBIN) in particular for high spectral resolution spectro-interferometric observations. The next generation of FT is intended to allow continuous fringe observation and to improve significantly the sensitivity of the interferometer. In this paper, a promising control approach is presented to cope with contradictory requirements. The FT system must be accurate and stable, which implies high frequency sampling of the optical path differences introduced by the atmosphere and the interferometer vibrations. It must also be as sensitive as possible, which needs to minimize the sampling frequency. The optimum between these concurrent requirements must be maintained through atmospheric and instrument conditions that change very rapidly. The proposed approach considers a discrete time feedback system and the controller design is based on H-infinity optimization. This approach provides the best trade-off between the largest sampling time and the validity of the discrete time feedback system. It is also well-suited to mitigate the vibrations. The effectiveness of the presented approach is illustrated through dedicated simulations involving a realistic case study : parameters for VLTI on AT, photon and detector noise, and identified frequencies of vibrations.

9907-83, Session PSWed

Multi-baseline chain bootstrapping with new classic at the NPOI

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Imaging with optical interferometers requires fringe measurements on baseline long enough to resolve the target. These long baselines typically have low fringe contrast. Phasing them requires fringe tracking on shorter baselines which typically have greater fringe contrast and combining the fringe-tracking signals on the short baselines to phase the long baselines in a baseline bootstrapping configuration. On long resolving baselines coherent integration also becomes necessary in order to shorten the integration time. This paper addresses both the baseline bootstrapping and the coherent integration. The Navy Precision Optical Interferometer (NPOI) is laid out in a way which permits long-baseline phasing from shorter baselines in a multi-baseline scheme. The New Classic instrument for NPOI was designed specifically to implement the multi-baseline bootstrapping capability and multi-baseline observations can now be carried out routinely at the NPOI. This paper provides details about the bootstrapping scheme at NPOI and shows some initial results. We also discuss the bootstrapping error budget, describe our new Bayesian coherent integration algorithm and compare its performance to theory.

9907-84, Session PSWed

The Kalman controller of the GRAVITY fringe tracker

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GRAVITY is a second generation interferometer for the VLTI. It combines 4 telescope beams together and is equipped with two combiners: one to correct the atmosphere and the other to do long exposure for high spectral resolution information. The beam combiner used for atmospheric correction is called the fringe tracker. It's nominal speed is 1kHz with a band-pass of 300Hz. The controller of the fringe tracker use the information from all 6 baselines to estimate the piston, and apply a correction on 4 piezos internal to GRAVITY. The controller is Kalman based, which estimate in real time the evolution of the atmosphere. It is a predictive algorithm which is used by the controller to anticipate the effect of piston variation, and apply the correction before it happens. We will present in this poster the Kalman controller, as well as first on-sky results obtained during the recent commissioning of the GRAVITY instrument.

9907-86, Session PSWed

The first light imaging C-RED infrared camera using the 320x256 Selex Saphira e-APD detector

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Developed by First Light Imaging and based on the Saphira HgCdTe APD detector developed by Selex, the C-RED infrared camera is offering the new APD (Avalanche Photo Diodes) disruptive technology in the area of infrared detectors for interferometry. This is in strong contrast to what is observed with APDs made out of III-V material or Si, which have typical excess noise factors of F~4-5 for III-V semi-conductors and F~2-3 for Si respectively. The exceptional characteristics of HgCdTe APDs are due to a nearly exclusive impaction ionization of the electrons, and this is why these devices have been called electrons avalanche photodiodes or e-APDs. These characteristics have inspired a large effort in developing focal plan arrays using HgCdTe APDs for low photon number applications such as active imaging in gated mode (2D) and/or with direct time of flight detection (3D imaging) and, more recently, passive imaging for infrared wave front correction and fringe tracking in astronomical observations. Use of e-APD arrays has already been reported for interferometric applications within the RAPID research programme (SPIE Montreal 2014, S. Guieu et al). C-RED is using the commercial SAPHIRA 320x256 24 microns pixel pitch HgCdTe e-APD array allowing to obtain sub-electron readout noise, taking advantage of the APD noise-free multiplication gain and non destructive readout ability of its readout circuit. C-RED is also capable of multiple regions of interest (ROI) readout allowing faster image rate (10's of KHz) while maintaining unprecedented sub-electron readout noise. The detector is placed in a sealed vacuum environment and cooled down to cryogenic temperature (90K) using a zero vibration integrated pulse tube, with a high reliability (MTBF > 90 000 h) which is much higher than standard Stirling coolers used usually with cooled infrared arrays. A cold filter and a cold pupil are used to limit the camera background, both are tunable for the needs of the application. Sensitive between 0.8 and 2.5 micron with the latest version of the Saphira detector, the C-RED camera offers a peak QE of 70% and can be operated up to 3500 frames per second with 16 bit data. The Cameralink full interface offers Ultra low latency data transmission to the control system, which is particularly useful for fast fringe tracking. Trigger input/output connectors are offered for synchronous operation of the camera.

Available by last quarter of 2015, the full C-RED camera design and performances will be presented in this paper.

9907-87, Session PSWed

Final performance of the GRAVITY detector systems

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GRAVITY is a second generation instrument for the VLT Interferometer,

designed to enhance the near-infrared astrometric and spectro-imaging capabilities of VLTI. The GRAVITY instrument uses all together five eAPD detectors, from which four for wavefront sensor, one for the Fringe tracker. In addition two Hawaii2RG are used, one for Acquisition camera and one for the spectrometer. A compact bath cryostat is used for each WFS unit, one for each of the VLT Unit Telescopes. Both Hawaii2RG detectors have a cutoff wavelength of 2.5 microns.

A new and unique element of GRAVITY is the use of infrared wavefront sensors. For this reason SELEX-Galileo has developed a new high speed avalanche photo diode detector for ESO. The SAPHIRA detector, which stands for Selex Avalanche Photodiodes for High-speed Infra Red Applications, has been already evaluated by ESO. At a frame rate of 1 KHz a read noise of less than one electron could be demonstrated.

9907-88, Session PSWed

Frequency stability characterization of a fiber Fabry-Perot interferometer

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A fiber Fabry-Perot (FFP) interferometer consists of a short piece of single mode optical fiber with highly reflective coatings on the end facets. For stability the FFP is encased in a thermally stabilized ferrule. Light is coupled both into and out of the interferometer with butt-coupled single mode optical fibers. When illuminated by a white light source, the FFP output is a broad array of optical frequency markers that can serve as a simple and robust spectroscopic calibration source for precise radial velocity (RV) measurements. In previous work we have demonstrated the potential benefits of such an FFP for <1 m/s RV short-term measurements at the Apache Point Observatory Galactic Evolution Experiment (APOGEE) instrument. Here we report a full laboratory-based characterization of an FFP that we have constructed for operation in the 750-1350 nm spectral region.

We use a pair of tunable continuous wave (CW) lasers at 1319 and 1064 nm (227 and 282 THz) to simultaneously measure and track the positions of the modes of an FFP having free spectral range, FSR = 41 GHz (0.33 nm), and finesse, F = 100. While the FFP is held at constant temperature, the 1064 and 1319 nm lasers are scanned across FFP resonances, and the optical power transmitted through the cavity from each laser is photodetected and digitized. Simultaneously, the frequencies of the two CW lasers are measured and recorded with respect to an atomically-stabilized laser frequency comb, which provides absolute stability at the sub-kilohertz level (<0.1 mm/s equivalent RV). The transmission signals have a Lorentzian functional form and the fit residuals reveal a centroid precision of ~1 MHz, limited by the achieved signal-to-noise ratio in a single 100 s frequency scan.

Using this technique we accurately determine the sensitivities of the FFP transmission peaks to temperature, optical power and input polarization. Of particular significance, our results demonstrate a means to characterize and correlate environmentally-driven perturbations of and among the FFP transmission modes across broad spectral bandwidths. For example, our approach will allow us to determine if the temperature dependence of the FFP mode frequencies is a linear function of frequency, or if other factors must be considered (such as wavelength dependence of dispersion or material thermo-refractive properties) in assessing the relative stability and frequencies of the FFP modes. These results and the techniques we introduce should have significance not only for passive etalons, but for a variety of actively-stabilized etalon spectral calibration sources that are proposed or are presently being constructed.

9907-89, Session PSWed

Experimental demonstration of a crossed cubes nuller for coronagraphy and interferometry

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In this communication are presented the first experimental results obtained on the Crossed-cubes nuller (CCN), that is a new type of Achromatic phase shifter (APS) based on a couple of crossed beamsplitter cubes. We review the general principle of the CCN, now restricted to two interferometric outputs for achieving better performance, and describe the experimental apparatus developed in our laboratory. It is cheap, compact, and easy to align. The results demonstrate a high extinction rate in monochromatic light and confirm that the device is insensitive to its polarisation state. Finally, the first lessons from the experiment are summarized and discussed in view of future space missions searching for extra-solar planets located in a habitable zone, either based on a coronagraphic telescope or a sparse-aperture nulling interferometer

9907-90, Session PSWed

Khayyam: progress and prospects of coupling a Spatial Heterodyne Spectrometer (SHS) to a Cassegrain telescope for optical interferometry

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In the temporal study of faint, extended sources at high resolving power, Spatial Heterodyne Spectrometer (SHS) can offer significant advantages about conventional dispersive grating spectrometers. SHS produces integrated spectra over a wide field-of-view (FOV from few arcsec to about one degree) in high spectral resolution (R about 105) using no (or a small < 1m) primary mirror. SHS's layout is a compact two-beam cyclical interferometer, and it produces wavenumber dependent 2-D Fizeau fringe pattern from which an input spectrum can be obtained via a Fourier transform. The architecture of SHS combines the high étendue of a Fourier Transform Spectrometer (FTS) with higher optomechanical tolerance and simpler optomechanical design associated with grating spectrometers.

Here, we describe a four-year continuous progress toward development of a prototype reflective SHS instrument-telescope configuration to combine all of the capabilities necessary to obtain high resolving power visible band spectra of diffuse targets from small aperture on-axis telescopes where significant observing time can be obtained. This instrument, Khayyam, is a tunable all-reflective spatial heterodyne spectrometer (TSHS) that is mounted to a fixed focal plane shared by the 0.6m Coude Auxiliary Telescope at Lick Observatory, CA. Khayyam has up to 55 arcsec input field of view, resolving power up to 176000, and a tunable bandpass covering ???>100nm. Khayyam was field tested to study spatially extended astronomical targets where high resolving power is necessary to separate multimodal signals, crowded molecular bands, and to sample low (<10 km/s) velocities at rapid temporal cadence. Here we will discuss the design considerations going into this new system, installation, testing of the interferometer-telescope combination, the technical challenges and plans.

9907-92, Session PSWed

Progress in two-dimensional far-IR double-Fourier modulation: a test bed with a rotating collimated source

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We present recent developments in the shorter wavelength upgrade of the Far-IR double-modulation testbed originally working between 300 microns and 3mm. With the replacement of the original beam-combiner with a high-frequency metal-mesh beam combiner and improved metrology, the testbed is now working in a narrow atmospheric band (21-27 microns) and performs spectro-spatial interferometer efficiently and with sufficient precision to extract and analyse a number of higher precision system non-ideal behaviours. In this presentation we show the recent improvements in the testbed development, the data algorithms applied and verification, the optical analysis of the phase distribution for non-ideal optics and finally, the implementation of an asymmetric calibration source placed in a rotating mount centred at the focus of a collimator which together act as a sky simulator. The rotation of the latter allows to simulate the rotation of the two-telescope variable baseline to generate the equivalent of a 2-D uv coverage and apply reconstruction algorithms to produce the first 2D FIR double-Fourier reconstructed images.

9907-93, Session PSWed

Results from a multi-aperture Fizeau interferometer ground test bed: demonstrator for a future space-based interferometer

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The construction of a space-based, long-baseline, far-infrared, imaging interferometer represents one of the most difficult challenges of the coming decades in Astrophysics. One of the solutions envisioned is the hyper-telescope which concept is based on a multi-aperture interferometer with more than two elements, arranged on kilometric-large baselines. The entrance pupil consists on several free-flying satellites, each one carrying a single mirror segment that is aligned and phased in a shape equivalent to a filled aperture of a kilometer in diameter. All these segments direct the light towards a common secondary collector, which is carried by an additional satellite, containing the necessary optics needed to recombine all the beams into a common focus. This will allow, thanks to accurate data processing, to image astronomical objects with a resolution equal to the longest baseline permitted by the interferometer's design.

In the framework of the European FP7-FISICA (Far Infrared Space Interferometer Critical Assessment) program, we developed a miniaturized version of the hyper-telescope to demonstrate multi-aperture interferometry on the ground. The demonstrator consists in a miniaturized version of a sparse-aperture system that mimics that of a space interferometer with a highly diluted collecting area. This would be ultimately integrated into a CubeSat platform, therefore providing the first real demonstrator of a Fizeau interferometer in space. Overall, the project objective is to prove its image reconstruction capabilities using a CubeSat platform to image bright celestial bodies outside Earth's atmosphere. The concept consists in a pupil mask with seven apertures, with a distribution optimized to provide a non-redundant coverage of the u,v plane followed by a lens which focalizes the interferometric images on a CCD camera. The mask is then rotated to generate the data set used to reconstruct the real image. This experiment in particular, is designed to test the suitability of such a design, optimize the mask's aperture layout and select the best manufacturing process.

In this paper we give a description of the instrument and present the results of the tests conducted both indoor, with a rectangular source, and outdoor using the Sun as target. We describe the image processing pipeline and the algorithm used to reconstruct the object image. To enforce the reliability of the software, a comparison with synthetically generated interferometric images is made, showing good agreement with the ones obtained experimentally. In addition, as a scientific application, we use aperture synthesis techniques to fit a limb-darkening model to our data and provide a measurement of the Sun diameter. Finally, we propose a first design of such an instrument implemented into a CubeSat platform.

9907-94, Session PSWed

Fiber-based heterodyne infrared interferometry: an instrumentation study platform on the way to the proposed Infrared Planet Formation Imager

Felipe E. Besser, Clemente Pollarolo, Miguel I. Pina, Ernest A. Michael, Univ. de Chile (Chile)

We present concept and first experimental lab results for a low-cost near-infrared heterodyne interferometer based on commercial 1.55μm fiber components with relative phase-stabilization between both telescopes, near to shot noise heterodyne detection with ambient temperature operated photodiodes, an ultra-coherent and noise-reduced fiber laser, and an FPGA-based digital correlator of 1 GHz bandwidth. After we will have advanced to a first demonstration with two and then three 14"-telescopes, the concept should be upgradable to connect larger numbers of mid- or large-class telescopes. Given that the employed fiber phase stabilization scheme should enable the operation of long baselines, we discuss the applicability of this concept for long-baseline, high telescope number systems (scalability of the concept) and mid-infrared wavelength. This could finally result in contributions to the design of the large infrared Planet Formation Imager which is being proposed currently.

9907-95, Session PSWed

Near infrared nulling interferometry: performance and results the Palomar fiber nuller and future possibilities

Eugene Serabyn, Jet Propulsion Lab. (United States)

Nulling interferometry at near-infrared wavelengths has advanced markedly over the past several years, proving its ability to provide unique high-contrast astronomical observations at small angles from bright stars. The Palomar Fiber Nuller has been the basis of several of these advances, including the use of a single mode fiber beam combiner, and the development of the statistical null self calibration approach to astrophysical null depth extraction, which has essentially done away with the need for fringe stabilization beyond that provided by an extreme adaptive optics system. These techniques have yielded high-accuracy on-sky nulls, and have enabled a unique survey for near-infrared exozodiacal emission that complements other observations. These demonstrated techniques, as well as several other new approaches to be discussed, now

allow us to consider next steps for near-infrared nulling interferometry. In particular, the incorporation of very simple nullers into facility high-contrast imaging coronagraphs at large astronomical telescopes now seems a feasible route forward.

9907-96, Session PSWed

First results obtained with the self-coherent camera at Palomar Observatory

Jacques-Robert Delorme, Observatoire de Paris (France) and Lab. d'Etudes Spatiales et d'Instrumentation en Astrophysique (France); Raphaël Galicher, Pierre Baudoz, Observatoire de Paris (France) and Lab. d'Etudes Spatiales et d'Instrumentation en Astrophysique (France); Dimitri Mawet, California Institute of Technology (United States); Eugene Serabyn, Jet Propulsion Lab. (United States); Johan Mazoyer, Space Telescope Science Institute (United States); James K. Wallace, Jet Propulsion Lab. (United States); Olivier Dupuis, Observatoire de Paris (France) and Lab. d'Etudes Spatiales et d'Instrumentation en Astrophysique (France)

During the last few years, the imaging of circumstellar disks and exoplanets has become one of the priorities to constraint models of planetary system formation and of planetary atmospheres. However, direct imaging of faint sources around bright objects is very challenging. The study of such objects therefore requires dedicated techniques such as coronagraphs that attenuate the light from the host star. However, because of phase and amplitude aberrations, a part of the stellar light reaches the detector and form speckles brighter than most of planets in the science images. Behind ground-based telescopes most of the speckles are due to the atmosphere turbulence. These dynamic wavefront errors are estimated and corrected by conventional adaptive optics (AO) systems that measure the wavefront error using a wavefront sensor in a dedicated optical channel. Because of the beam splitting, quasi-static non-common path aberrations (NCPA) are generated by the instrument optics between the wavefront sensing channel and the science image channel, which limits the accuracy of the AO correction.

VLT/SPHERE and Gemini/GPI are two instruments designed to detect young Jupiter-like planets. They minimize the quasi-static NCPA in open loop before the observations but cannot control them during the observations. However, as NCPA evolve during the observations, the calibration degrades with time and the contrast performance is limited by quasi-static speckles to 1e-4 ~ 1e-5 at 0.5'' in raw images. Space-based telescopes are atmosphere turbulence free but the variations of temperature and gravity also induce quasi-static aberrations. In order to reach higher contrast it is thus mandatory to estimate and compensate them in closed loop during the observations.

Our team proposes the use of the Self-Coherent Camera (SCC) as a focal plane wavefront sensor (FPWFS). It is a non invasive device based on spatial modulation of speckles. Unlike techniques based on temporal modulation, the SCC is able to estimate and correct speckles using only one focal plane image.

In laboratory, we can reach contrast levels of 2e-8 at a few ?/D in monochromatic light (? = 635 nm) and contrast levels of 4.5e-8 between 5 and 17 ?/D in polychromatic light (?? = 80nm around ? = 635 nm).

Attractive features and laboratory performance of the SCC led us to move on to the next stage of development. That is precisely what we do. Indeed, since spring 2015, we developed collaboration with Palomar team to test the SCC on sky.

During this presentation I will present first results obtained on sky with the SCC on the stellar double coronagraph bench.

9907-97, Session PSWed

Automated alignment and closed loop guiding of multiple telescope beams

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Atmospheric turbulence and telescope pupil motions are the two major challenges in implementing long baseline interferometric astrometry (Lacour et al. 2014, A&A). The telescope beams enter a coherent beam combiner via optical delay lines of the interferometric laboratory. These beams usually contain field tip-tilts due to atmospheric seeing and pupil motions caused by the optical train vibrations while tracking the object of interest. Previous projects (the Keck Outrigger astrometry, the ESO's PRIMA) have shown that difficulties can arise in the astrometry measurements if an efficient pupil tracking and stabilization mechanism is not implemented.

GRAVITY is a powerful interferometric imaging (4 milliarcseconds) and precise astrometric instrument (10 microarcseconds) and has been installed at the Very Large Telescope Interferometer (VLTI) of ESO. Due to the field and pupil errors, the performance of GRAVITY can be severely limited in two ways: a) coupling efficiency of stars light injection into single mode fibers, which carry the beams for coherent beam combination; b) astrometric errors. The precise astrometry requires the field and pupil stabilization to be implemented within 2 milliarcseconds RMS and 4 millimeters RMS at the UT (8 m) scale. A multiple beam guiding instrument, acquisition camera, has been built to meet these challenges for the GRAVITY beam combiner and for the fringe tracker. It tracks efficiently the pupil, field and higher order aberrations of four VLTI beams simultaneously, for every 1 s. Thereby it enables: a) active pupil and field stabilization; b) stabilization of star light injection into single mode fibers; c) characterization of wavefront profile and defocus correction.

The acquisition camera has four optical functions: a) pupil tracker: images four pupil reference lasers using 2 x 2 lenslets that are mounted on the spiders of telescope secondary mirror; b) field tracker: images science field; c) pupil imager: reimages telescope pupil; d) aberration tracker: implements a Shack-Hartmann image.

The detector images are analyzed with a dedicated data reduction software to extract tip-tilts of stars from the field tracker image, pupil motions (lateral and longitudinal) from the pupil tracker image and wavefront higher order aberrations from the Shack-Hartmann image.

The measured field and pupil measurements are used in two ways: a) for the alignment of GRAVITY with the VLTI; b) for the field and pupil stabilization. The wavefront aberrations are currently being used for an engineering purpose and defocus correction. In future, these can be used for non-common path errors correction. The pupil imager is used to visually monitor the pupil during the observations.

The validity of the design and the concepts of the acquisition camera are demonstrated with the telescope beams generated with GRAVITY calibration unit and also at the observatory during commissioning phase of GRAVITY. Currently it is successfully operational in the closed loop beam guiding. The instrument concepts and the characterization results are detailed.

The work carried out here leads to the PhD thesis of Anugu.

9907-98, Session PSWed

Recent developments with the Visible Nulling Coronagraph

Brian A. Hicks, Richard G. Lyon, NASA Goddard Space Flight Ctr. (United States); Peter Petrone III, Sigma Space Corp. (United States); Matthew R. Bolcar, Mark Clampin, NASA Goddard Space Flight Ctr. (United States); Michael A. Helmbrecht, Iris AO, Inc. (United States); Udayan Mallik, NASA Goddard Space Flight Ctr. (United States); Ian J. Miller, LightMachinery Inc. (Canada)

A wide array of general astrophysics studies including detecting and characterizing habitable exoplanets could be enabled by a future large segmented UV-Optical-Infrared (UVOIR) telescope. In order to achieve the sensitivity for studying a habitable planet through direct imaging, such an observatory would be paired with a starshade or internal coronagraph for broadband starlight suppression to reach off-axis contrasts exceeding a billion to one – a formidable challenge for any high-contrast imaging system. Over the past several years, a laboratory-based Visible Nulling Coronagraph (VNC) has evolved to reach requisite contrasts over a ~ 1 nm bandwidth at narrow source angle separation using a segmented deformable mirror in one arm of a Mach-Zehnder layout. More recent efforts presented here target broadband performance following the addition of two sets of half-wave Fresnel rhomb achromatic phase shifters (APS) with the goal of reaching 10?9 contrast, at a separation of 2l/D, using a 40 nm (6%) bandwdith single mode fiber source. New developments in this broadband nulling effort will be presented along with example considerations for future long-term application.

9907-38, Session 17

Imaging transient events at high angular resolution *(Invited Paper)*

Gail H. Schaefer, Georgia State Univ. (United States)

Resolving the spatial structure of transient events provides insights into their physical nature and origin. Recent observations using long baseline optical/infrared interferometry have revealed the size, shape, and angular expansion of bright novae within a few days after their outbursts. This has implications for understanding the timescale for the development of asymmetric features in novae ejecta. Additionally, combining spectroscopic measurements of the expansion velocity with the angular expansion rate provides a way to measure a geometric distance to the nova. I will provide a review of interferometric observations of novae, with a focus on recent results of the expansion and spatial structure of Nova Del 2013. I will also discuss other promising applications of interferometry to transient sources, such as measuring the image size and centroid displacements to measure planetary masses in gravitational microlensing events. Given the timescales of transient events, it is critical for interferometric arrays to respond rapidly to targets of opportunity in order to optimize the instrumental sensitivity and baselines required to resolve the source while its brightness and size change over time.

9907-39, Session 18

Fast sub-electron detectors review for interferometry *(Invited Paper)*

Philippe Feautrier, Institut de Planétologie et d'Astrophysique de Grenoble (France); Jean-Luc Gach, First Light Imaging S.A.S. (France) and Lab. d'Astrophysique de Marseille (France)

New disruptive technologies are now emerging for detectors dedicated to interferometry. The detectors needed for this kind of applications need antonymic characteristics: the detector noise must be very low, especially when the signal is dispersed but at the same time must also sample the fast temporal characteristics of the signal. This paper will describe the new fast low noise technologies that have been recently developed for interferometry and adaptive optics. The presentation will be didactic and will present the operation of these new detectors.

The first technology is the Avalanche PhotoDiode (APD) infrared arrays made of HgCdTe. I will present the two programs that have been developed in that field: the Selex Saphira 320x256 and the 320x255 RAPID detectors developed by Sofradir/CEA LETI in France. Status of these two programs and future developments will be presented. Sub-electron noise can now be achieved in the infrared using this technology. The exceptional characteristics of HgCdTe APDs are due to a nearly exclusive impaction ionization of the electrons, and this is why these devices have been called electrons avalanche photodiodes or e-APDs. These characteristics have inspired a large effort in developing focal plan arrays using HgCdTe APDs for low photon number applications such as active imaging in gated mode (2D) and/or with direct time of flight detection (3D imaging) and, more recently, passive imaging for infrared wave front correction and fringe tracking in astronomical observations. In addition, a commercial camera called C-RED, based on Selex Saphira and commercialized by First Light Imaging, will be presented.

Some groups are also working with instruments in the visible. In that case, another disruptive technology is showing outstanding performances: the Electron Multiplying CCDs (EMCCD) developed mainly by e2v technologies in UK. The OCAM2 camera, commercialized by First Light Imaging, uses the 240x240 EMMCD from e2v and is successfully implemented on the VEGA instrument on the CHARA interferometer (US) by the Lagrange laboratory from Observatoire de la Cote d'Azur. By operating the detector at gain 1000, the readout noise is as low as 0.1 e and data can be analyzed with a better contrast in photon counting mode.

In conclusion, the development of new detectors dedicated to fast applications is offering sub-electron readout in the visible and in the infrared, opening a new era in terms of sensitivity to the detectors for interferometry.

9907-40, Session 18

Progress towards photon-counting infrared arrays for interferometry

David F. Buscher, Eugene B. Seneta, Xiaowei Sun, John S. Young, Univ. of Cambridge (United Kingdom); Gert Finger, European Southern Observatory (Germany)

The advent of low-dark-current eAPD arrays in the near infrared ushers in the possibility for photon-counting, high quantum efficiency detectors at these wavelengths. Such detectors would revolutionise the sensitivity of interferometry because near-infrared wavelengths are at the "sweet spot" between the corrupting effects of atmospheric seeing at shorter wavelengths and thermal noise at longer wavelengths. We report on laboratory experiments with cooled Selex SAPHIRA detectors aimed at demonstrating photon-counting performance with these devices by exploiting enhanced avalanche gain and multiple non-destructive readouts. We explain the optimum modes for employing these detectors in interferometry.

9907-41, Session 19

Opportunities for interferometric studies of disk-eclipsed binary star systems *(Invited Paper)*

Robert Stencel, Univ. of Denver (United States)

As sky surveys document an increasing number of transient celestial phenomena, an intriguing subset of objects are emerging that show variations in brightness, interpretable as the transit of a circumstellar disk in front of a companion star in a binary system. The brightest member of this class is the F0 supergiant + disk system epsilon Aurigae, along with more than a dozen new candidates sharing similarities. Well-known cases include EE Cep, BM Ori and KH15D. Characteristics of all of these will be discussed in terms of their suitability for interferometric study. Next generation interferometric imaging offers the potential to detect disk structure features that are driven by dynamical forces, chemical transitions and thermal gradients. These include observable effects of tidal spiral density waves, dust and planetessimal formation/evolution in disks, and orbital phase-dependent heating of the disk by the external companion star - see http://adsabs.harvard.edu/abs/2015ApJ...798...11P .

9907-42, Session 20

Astrophotonics in the context of optical/IR interferometry *(Invited Paper)*

Lucas Labadie, Univ. zu Köln (Germany); Jean-Philippe Berger, European Southern Observatory (Germany); Nick Cvetojevic, The Univ. of Sydney (Australia); Sylvestre Lacour, Observatoire de Paris à Meudon (France); Guillermo Martin, Institut de Planétologie et d'Astrophysique de Grenoble (France); Stefano Minardi, Friedrich-Schiller-Univ. Jena (Germany); Guy S. Perrin, Observatoire de Paris à Meudon (France); Martin M. Roth, Leibniz Institute for Astrophysics Potsdam (Germany); Robert R. Thomson, Heriot-Watt Univ. (United Kingdom)

In the era of large telescopes and multi-aperture interferometer, the increasing complexity of the hosted instruments poses new challenges to astronomers. "Complexity" encompasses here issues related to size and weight, nature of the required optical functions in imaging and spectroscopy, mechanical and thermal stability, versatility, age reliability and cost-driven requirements. Astrophotonics, a relatively young field at the interface between photonics and astronomical instrumentation, has grown significantly in the last decade, enabling radically new solutions in response to the need for advanced instrumentation. Interferometry and spectroscopy techniques represent prime beneficiaries from these new technologies, as for instance in the case of the near-infrared interferometric instrumentation at the VLTI.

In this paper, we first review some fundamental aspects of photonic science which drove the emergence of astrophotonics, namely the conditions for low-loss guiding, the modal properties of waveguides, the achievable optical passive or active functions, the chromatic boundaries and the associated fabrication technologies. We emphasize the diversity of optical designs that astrophotonics allows, from the simplest photons passive combiner to some more visionary concepts of integrated spectrographs, laser sources or detectors. We highlight what the effective outcome has been for observational astrophysics, in particular in the field of high angular resolution, and we analyze the prospects for further technological development also considering the potential synergies with other fields of physics, where specific needs may result in a direct return for astronomy (e.g. non-linear optics in condensed matter physics). We also stress the central role of fiber optics in routing and transporting light, delivering complex filters, or interfacing instruments and telescopes, more specifically in the context of a growing usage of adaptive optics. We believe astrophotonics has a unique role to play in the forthcoming era of new ground-based astronomical facilities, and possibly in the field of space science, which is strongly driven by high-maturity low-risk instrumental solutions.

9907-43, Session 20

Increasing the spectral coverage of interferometric integrated optics: K/L and N-band laser-written beam combiners

Jan Tepper, Univ. zu Köln (Germany); Romina Diener, Friedrich-Schiller-Univ. Jena (Germany); Lucas Labadie, Univ. zu Köln (Germany); Stefano Minardi, Friedrich-Schiller-Univ. Jena (Germany); Balaji Muthusubramanian, Univ. zu Köln (Germany); Jörg-Uwe Pott, Max-Planck-Institut für Astronomie (Germany); Alexander Arriola Martiarena, Macquarie Univ. (Australia); Gillian E. Madden, Debaditya Choudhury, William N. MacPherson, Robert R. Thomson, Heriot-Watt Univ. (United Kingdom)

The recent advent of Gravity at the VLTI, preceded by the significant scientific outcome of PIONIER, strongly suggests that the small-scale and stiff integrated optics concept in interferometry is a very promising one, either for scientific observations or fringe tracking operations, and may well become mainstream whenever the beams of more than four telescope are to be interferometrically recombined. This platform has been so far very successful at near-IR wavelengths shorter than 2.2 microns. For wavelengths longer than 2.4 microns, alternatives to silica-based technologies need to be implemented. Solutions based on chalcogenide glasses are following slow but constant maturation. Over the last years, it has been shown that laser writing technique in IR chalcogenide glasses is a valuable solution for the mid-IR range. These glasses are transparent up to 10μm and the ultrafast laser writing technique allows light-guiding structures to be written in 3D in the glass substrate. Therefore, such chips simultaneously open a new wavelength range for integrated optics and support a more flexible 2D arrangement remapping of the chip output. Previous work has demonstrated the proof-of-concept at 10 microns.

In this paper we extend, in the context of our ALSI project (Advanced Laser-writing for Stellar Interferometry), our work on chalcogenide-based mid-IR integrated optics to both the K and L bands, a spectral range where modal filtering and integrated beam combination is particular valuable, but have not yet been experimentally explored using laser writing techniques. We have investigated the properties of beam combiners based on commercial GLS glass and conducted a series of measurements. We fabricate 2-telescope directional couplers for which we measure the reachable interferometric contrast in the lab to >90%. Progress is being made towards components combining more sub-apertures. We demonstrate the single-mode properties of the sample at 3.4 microns and investigate the spectral splitting ratio of our directional couplers, which is an important parameter for broadband operation. We also measure the low-level of birefringence of the laser-written components by measuring no significant alteration of the polarization state of a HeNe Laser at 3.39μm for a statistically significant set of waveguides with different writing parameters. In the context of this work, the propagation losses for L band laser written waveguides have been demonstrated to be as low as 0.25 dB/cm, which are among the lowest measured so far. We have also studied the option of a fiber-fed component using commercial fluoride fibers, and we find that the fibers are likely the limiting sub-system in terms of degradation of the light polarization. We finally verify the thermal behavior of the components after undergoing different cooling cycles. We draw first conclusions on the potential of chalcogenide integrated optics components for stellar interferometry in a wavelength range which is essential to address relevant questions for the understanding of planet formation and the physics in in young stellar objects. We believe this is a step forward in the maturation of integrated optics concepts for mid-IR interferometry.

9907-44, Session 20

ALOHA project: how nonlinear optics can boost interferometry to propose a new generation of instrument for high-resolution imaging

François Reynaud, Pascaline Darré, Ludovic Szemendera, Ludovic Grossard, Jean-Thomas Gomes, Laurent Delage, XLIM Institut de Recherche (France)

The ALOHA research program aims to propose a breakthrough generation of instrument for high resolution imaging in astronomy in the infrared spectral domain. This fully innovative concept arises from our simultaneous competence in nonlinear optics and high resolution imaging with telescope arrays. Acting like a mixer in a radio receiver, the nonlinear process (sum frequency generation) shifts the infrared radiations emitted by the observed astrophysical source to a NIR or visible spectral domain. This way, the light beam is more easily processed by mature optical devices and detectors.

The purpose of this talk, will be to make a presentation of the concept and an overview of progresses of the ALOHA project. The general principle of frequency conversion implemented in the interferometric arms of a stellar interferometer will be described and a focus will be laid on the technological inputs. By shifting the astronomical spectrum into a propitious spectral domain compatible with the use of silica fibers, we propose to use an instrumental chain working in a technologically-mature wavelength of telecom windows. This completely new approach allows to design a new generation of instrument ables to address the problem of the mid-infrared high resolution imaging very informative for astrophysical studies (Active Galaxy Nuclei, Young Star Objects, exoplanets...).

In this new concept, the key point is the possibility to convert the light from a mid-infrared radiation to the visible / near infrared range through an "up-conversion stage". For this purpose it is possible to use nonlinear optics taking care that the nonlinear process makes necessary the use of intense pump copropagating with the faint astronomical beam. As the imaging process uses a spatial coherence analysis, the up conversion stage has to preserve the mutual coherence of the waves and to operate with a minimum additional noise. On the other hand, there are several advantages of using such a frequency conversion, especially from mid-infrared to near-infrared or visible wavelengths: the possibility of using spatially single-mode and polarization maintaining components which are easy to handle and have low optical losses (optical fibers and integrated optical combiners), the availability of efficient detectors (high quantum efficiency, low noise, room temperature operation) and not to be compelled to use complex cooling systems over the entire instrument (assuming that the frequency conversion takes place right after the telescope focus).

In this framework, an historic overview of the different experimental steps overcome in the last decade will be proposed in order to give an exhaustive description of the current potential of the ALOHA project.

This paper will be introductive to two other papers:

The first one on the implementation of the ALOHA @1.55 µm prototype on the CHARA array with an evaluation of the potential results for on-sky observation in H band.

The second one on in lab experimental development in the L band up to photon counting regime.

9907-45, Session 21

Evolved stars at high angular resolution: present and future *(Invited Paper)*

Claudia Paladini, Univ. Libre de Bruxelles (Belgium)

The late evolutionary stages of stellar evolution are a key ingredient for our understanding in many fields of astrophysics, including stellar evolution and the enrichment of the interstellar medium (ISM) via stellar yields.

Already the first interferometric campaigns identified evolved stars as the primary targets because of their extended and partially optically thin atmospheres, and the brightness in the infrared.

Interferometric studies spanning different wavelength ranges, from visual to mid-infrared, have greatly increased our knowledge of the complex atmospheres of these objects where different dynamic processes are at play. In less than two decades this technique went from measuring simple diameters to produce the first images of stellar surfaces.

By scanning the extended atmospheres we constrained theoretical models, learnt about molecular stratification, dust formation, and stellar winds, and there is still a lot to be done.

In this contribution I will review the recent results that optical/infrared interferometry has made on our current understanding of cool evolved stars. The presentation will focus on red giant branch (RGB) stars, asymptotic giant branch (AGB) stars, and red supergiants (RSGs).

I will discuss the challenges of image reconstruction, and highlight how this field of research will benefit from the synergy of the current interferometric instrument(s) with the second generation VLTI facilities GRAVITY and MATISSE. Finally I will conclude with a short introspection on applications of a visible interferometer and of the the Planet Formation Imager (PFI) to the field of evolved stars.

9907-46, Session 22

Image reconstruction: techniques and results *(Invited Paper)*

Fabien Baron, Georgia State Univ. (United States)

Optical/near-IR interferometry now benefits from the availability of several stable image reconstruction packages, thanks to the large amount of development work undertaken in the last 5 years. Software initiatives such as the ANR Project POLCA and the Optical WP4 Joint Research Activity have especially stimulated research in Europe, with a focus on polychromatic reconstructions and sparse representations. In the US, image reconstruction has been driven by specific astronomical cases (e.g. rotating spotted stars), with a focus on compressed sensing and imaging on spheroids.

This talks gives a short yet complete overview of the software landscape, presenting all the state-of-the-art algorithms while also emphasizing the relevant science cases.

9907-47, Session 22

7th edition of the "interferometric imaging beauty contest" *(Invited Paper)*

Joel Sanchez, Max-Planck-Institut für Astronomie (Germany); Éric M. Thiébaut, Ctr. de Recherche Astronomique de Lyon (France)

Image reconstruction in optical interferometry has gained considerable importance for astrophysical studies during the last decade. This has been mainly due to the improvements of the imaging capabilities of the existing interferometers (e.g., PIONIER/VLTI, MIRC-6T/CHARA) and of the expected facilities in the coming years (e.g., GRAVITY and MATISSE at the VLTI or the Planet Formation Imager initiative). However, despite the advances made so far, image synthesis in optical interferometry is still an open field of research. Since 2004, the optical Interferometry community has organized a biennial contest to formally test the different methods and algorithms for image reconstruction. In 2016, we will celebrate the 7th edition of the "Interferometric Imaging Beauty Contest". This initiative is an open call to the community to participate in the reconstruction of a selected

set of simulated targets with a wavelength-dependant morphology as they could be observed by the current and coming instruments (e.g., MATISSE, GRAVITY or MIRC/CHARA). This contest will represent a unique opportunity to benchmark, in a systematic way, the current advances and limitations in the field, as well as to discuss the future lines of action. In this contribution, we will summarize: (a) the rules of the contest; (b) the different used data sets and how they were selected; (c) the methods and results obtained by each one of the participants; (d) the metric used to select the best reconstructed images and the winners of the contest.

9907-48, Session 22

Effective global optimization for image restoration in optical/IR interferometry

Férréol Soulez, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Éric M. Thiébaut, Observatoire de Lyon (France); Matthew Ozon, Jonathan Léger, Ctr. de Recherche Astrophysique de Lyon (France)

Many image reconstruction algorithms have been proposed to cope with optical/IR interferometric data. A first difficulty is to deal with the sparsity of the data and the uneven u-v coverage. This is usually overcome by imposing a priori constraints to the sought image. The reconstruction then amounts to solving an optimization problem where fidelity to the data and to the priors must both be satisfied to a chosen level. Due to the type of interferometric measurements, the image restored by the current algorithms depends on some initial guess and on the optimization strategy. Even though the resulting image is often satisfactory, there are no guarantees that the best image is obtained given the data and the constraints. This is a strong defect which may badly impact the interpretation of interferometric observations by astronomers. We propose a new image reconstruction approach where a minimum amount of unmeasured data is introduced to make the image reconstruction process a convex problem whose solution is thus unique. Then, combining the convex image reconstruction and a Monte Carlo strategy to sample the unmeasured data, it is possible to retrieve a much better solution in a reasonable computational time. Compared to previously proposed global optimization strategies, e.g. based on Monte Carlo Markov Chain (MCMC), our approach has a very limited number of variables to sample randomly (i.e. much less than the number of pixels) which explain its effectiveness. We demonstrate on a number of cases the advantages of our strategy implemented in MiRA algorithm. The proposed method is completely flexible and can be extended to any kind of data and priors, in particular the case of multi-spectral image reconstruction is considered.

9907-100, Session PSTh

A new dual-channel speckle instrument for Gemini and WIYN

Nicholas J. Scott, Steve B. Howell, NASA Ames Research Ctr. (United States); Elliott P. Horch, Southern Connecticut State Univ. (United States)

GemSpec is a new dual-channel instrument based on the existing DSSI (Differential Speckle Survey Instrument), but the new instruments will have both speckle and “wide-field” imaging capabilities. Identical copies of the instrument will be installed on permanent loan at the Gemini-N and WIYN telescopes. A third instrument could potentially be added to the Gemini-S telescope. GemSpec is expected to be a versatile and high-demand community instrument. Many exoplanet targets will come from K2 and TESS as well as the already large number of RV exoplanets that will desire follow-up high-resolution imaging. Most of these stars will be brighter than R~13, excellent targets for the instrument at Gemini. The faint limiting magnitude, for speckle observations, will remain around 16 to 16.5 depending on observing conditions, while wide-field, high speed operation should be able to go to 21+. Each instrument will use two identical Andor iXon Ultra 888 EMCCD cameras for a blue reflective channel and a red transmissive channel. Additionally, Sloan g, r, i, and z filters will be available in wide field mode and narrow-band filters for speckle that have approximate center wavelengths similar to Johnson filters. The speckle field of view will be 2.4 x 2.4” while the wide-field mode will have an approximate field of view of 26 x 26”. Full frame readout of 26 frames per second is possible with much higher frame rates possible within subarrays for the speckle imaging mode. The instrument will be remotely operable via a VNC connection from either the mid-level facility at Hale Pohaku or Hilo. The instrument is expected to be an official visitor instrument, run in pre-designated observing blocks, or it may be permanently mounted at the telescope, to be operated in a queued observing mode. A speckle data reduction pipeline will be provided to the community. These new instruments will facilitate a wide range of science projects and fulfill observatory needs in the coming years.

9907-101, Session PSTh

COvariancE of Lucky Images (COELI): resolution limit as a function of the atmosphere conditions

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In this paper, we show a new algorithm which takes advantage of temporal fluctuations of the image intensity along a frame series to uncover possible companions surrounding the main star. If we consider a series of short-exposure images which have been selected applying the Lucky Imaging technique, the intensity of those pixels where a faint companion is placed will fluctuate in phase with the main star intensity along the image series. However, the pixels containing incoherent speckles will fluctuate in counter phase. Hence, for detecting hidden objects, it would be enough to find those pixels in the image series which fluctuate in phase with pixels gathering light from the main star. The technique is based on the estimate of the COvariancE of Lucky Images (COELI) for all the pixels contained in the image and it is appropriate for detecting objects placed in an area surrounding the host star within a radius of ?/r0, where r0 is the Fried parameter.

The image of a point source obtained by a perfect optical system is described by the Airy pattern. In ground-based telescopes this image consists of a central peak surrounded by a number of speckles whose temporal average is commonly known as halo. The central peak is due to the coherent part of wavefront energy whilst the surrounding speckle comes from the incoherent one. Hence, to increase the central peak energy it is enough to have a less aberrated incoming wavefront or to compensate it by an Adaptive Optics system. In this analysis, we will not consider the use of any Adaptive Optics system.

The procedure we followed was to calculate the normalized covariance given by the expression:

C[isp , i(r)] = Conv[isp , i(r)] / ?sp ?ir

The convolution product is given by:

Conv[isp , i(r)] = < isp i(r) > ? < isp > < i(r) >,

where isp stands for the star peak intensity, i(r) is the intensity detected at a position r from the star peak, ? is the standard deviation and <> is the ensemble average (frame series average).

The goal of this paper is to show the COELI performance when detecting faint objects close to the host star. In a recent paper we have applied COELI to a series of images taken by the CAHA 2.2 m telescope. The technique allowed us to detect a star companion at a distance as short as one Airy ring. This implies that, under certain conditions, the Rayleigh

diffraction limit can be reached from a 2.2 m ground-based telescope.

However, there are other parameters to be considered. In particular, we are interested in checking the influence of the atmosphere conditions on the capability of the technique for reaching the Rayleigh diffraction limit.

9907-102, Session PSTh

Sparse aperture masking with SPHERE

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Sparse Aperture Masking (SAM) has recently been commissioned on SPHERE, the VLT's new adaptive optics high resolution imager. SAM extends the capabilities of SPHERE by providing high contrast measurements at and beyond the traditional diffraction limit. SAM can be used in conjunction with each of the SPHERE sub-instruments, allowing dual band imaging in the visible and near-infrared, near-infrared integral field spectroscopy, and polarized differential imaging in the visible and near-infrared. We report on the results of commissioning, including the measured and expected performance and some early scientific results on nearby debris and transition disks.

9907-103, Session PSTh

Interferometric direct imaging properties of a BIGRE-DAM device in laboratory

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DAM (Discretized Aperture Mapping) is an original filtering device able to improve the performance in high angular resolution and high contrast imaging by the present class of large telescopes equipped with adaptive optics (Patru et al. 2011, 2014, 2015). By discretising the entrance pupil of a large telescope into an array of many coherent sub-apertures, DAM provides unique imaging and filtering properties by means of spatial filtering and interferometric techniques. DAM is a high spatial frequency filter able to remove part of the phase residuals in a wavefront. Moreover, the object-image convolution relationship is preserved on a finite field of view. DAM can be achieved either with a bunch of optical fibers, or an integrated optic, or simply with an innovative BIGRE micro-lenses array. BIGRE-DAM is a simple integrated optic component formed of an afocal double lenslet array (Antichi et al. 2009, 2011). This paper deals with the first in-lab experiment of a BIGRE-DAM device at visible wavelength. The optical properties of such component are shown, including both diffractive and interferometric effects. The interferometric pattern produced by the array of DAM reproduce the same diffractive pattern of the whole entrance aperture. However, the field of view is limited by interferometry due to the spatial aliasing effect, for which the field is periodically replicated across the image, preventing wide field on extended objects. We study the aliasing by imaging the point spread function (PSF) when observing a point-like object located either on-axis or at various off-axis positions across the field of view. The experimental results are in good agreement with the numerical simulations. The next objective will be to test a DAM with an adaptive optic system, first in laboratory and then on sky.

9907-104, Session PSTh

Combining super-resolution and spectroscopy in the visible with FIRST at Subaru: application to binary systems and evolved stars

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FIRST (Fibered Imager foR a Single Telescope) is a high resolution and high contrast instrument being developed by Observatoire de Paris. After a successful observing campaign of binary systems on the 3-m Shane telescope at Lick Observatory from 2010 to 2013, FIRST is now part of the the SCExAO project. FIRST has been integrated with the visible bench of SCExAO and is currently being commissioned as a visible module aiming at hitting the diffraction limit at visible wavelengths.

The principle of FIRST is based on the combination of aperture masking and spatial filtering. The pupil is divided into 37 sub-pupils that feed single mode fibers. 18 of them are recombined in two sets of nine fibers, positioned on a line with non-redundant spacings, thus avoiding the blurring of the fringes and allowing the cross-dispersion (spectral resolution of 300). This setup offers several advantages over the classical aperture masking technique, such as: (i) potentially better visibility accuracy thanks to the spatial filtering performed by the single-mode fibers, (ii) a better (u,v) plane coverage for the same size of sub-pupils, (iii) the capability of cross-dispersion with in-line recombination.

The optical and mechanical setup have been updated on several aspects (see Doughty et al., these proceedings). In this presentation, we report on our latest on-sky results obtained with FIRST at Subaru. We have observed and detected several binary systems, and in particular two tight binary systems with separation below the diffraction limit of the telescope (lambda/D = 15 mas at 600nm, the shortest wavelength of the spectral range): Alpha Equ with a separation of 11mas and contrast of 0.5 in the visible, and Alpha And with a separation of 11mas and contrast of 0.2. We will also show that with the fine angular resolution provided by FIRST, stellar disks of evolved stars are resolved at visible wavelengths. The data reduction is in progress and should soon allow to measure potential asymmetries in the surface brightness of the stars we have observed.

Coupling high angular resolution and spectral resolution in the visible, FIRST is a promising instrument in the context of the characterization of faint companions, in particular on the future extremely large telescopes. In the near future, the current classical recombination of FIRST will be upgraded with an integrated optics chip, thus dramatically improving the sensitivity and dynamic range (see Martin et al., and Gauchet et al., these proceedings).

9907-105, Session PSTh

Current standing and upgrades to FIRST at the Subaru Telescope

Danielle Doughty, The Univ. of Arizona (United States) and Subaru Telescope, National Astronomical

Observatory of Japan (United States); Elsa Huby, Univ. de Liège (Belgium) and Observatoire de Paris (France) and Lab. d'Etudes Spatiales et d'Instrumentation en Astrophysique (France); Lucien Gauchet, Observatoire de Paris (France) and Lab. d'Etudes Spatiales et d'Instrumentation en Astrophysique (France); Guy S. Perrin, Observatoire de Paris à Meudon (France) and Lab. d'Etudes Spatiales et d'Instrumentation en Astrophysique (France); Sylvestre Lacour, Observatoire de Paris (France) and Lab. d'Etudes Spatiales et d'Instrumentation en Astrophysique (France); Nemanja Jovanovic, Subaru Telescope, National Astronomical Observatory of Japan (United States); Gaspard Duchêne, Univ. of California, Berkeley (United States) and Ctr. National de la Recherche Scientifique (France) and Institut de Planétologie et d'Astrophysique de Grenoble (France); Franck Marchis, SETI Institute (United States); Julien Lozi, Subaru Telescope, National Astronomical Observatory of Japan (United States); Olivier Guyon, Subaru Telescope, National Astronomical Observatory of Japan (United States) and The Univ. of Arizona (United States)

FIRST (Fibered Imager foR a Single Telescope) is a current module developed by Observatoire de Paris on the SCExAO (Subaru Coronagraphic Extreme Adaptive Optics) instrument at the 8-m Subaru Telescope on Maunakea. FIRST is a visible interferometer working from 600-900 nm and makes use of techniques such as non-redundant pupil remapping, spatial filtering, and cross-dispersion. With these combined techniques FIRST is capable of both high resolution and high contrast imaging; thus, making it ideal for observing close binaries within the diffraction limit of telescopes, stellar disks of evolved stars, asymmetries in the surface brightness of stars, and in the future with ELTs and an upgrade to an integrated optic chip it will being capable of characterizing faint and low-mass companions (see Martin et al., and Gauchet et al., these proceedings). Recent results from a current campaign on the Subaru telescope are described elsewhere (see Huby et al., these proceedings).

The instrument since arriving at the Subaru telescope in 2013 from its binary star campaign at the 3-m Shane telescope at Lick Observatory, has been undergoing optical and mechanical upgrades to improve its stability and performance. This presentation will be focusing on these improvements as well as tests done in conjunction with a simulated model to identify the sources of the biases which has limited the capability of the previous generation instrument and the strategies used by our team to mitigate them.

9907-106, Session PSTh

Discretized aperture mapping for wavefront sensing

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DAM (Discretized Aperture Mapping) is an original filtering device able to improve the performance in high angular resolution and high contrast imaging by the present class of large telescopes equipped with adaptive optics (Patru et al. 2011, 2014, 2015). DAM is a high spatial frequency filter able to remove the problematic phase errors produced by the small scale defects in the wavefront. Various effects are related to the high-spatial frequency content which is neither seen by any wavefront sensor (WFS) nor corrected by any adaptive optic (AO) and is transmitted up to the final detector. In particular, any wavefront sensor, due to its finite sub-apertures size, is fundamentally limited by the well-known aliasing effect, where high spatial frequencies are seen as spurious low frequencies. DAM can be used as an anti-aliasing filter in order to improve both the accuracy of the WFS measurements and the stability of the AO compensation. This paper deals with a new spatially filtered wavefront sensor, named DAM-WFS, where DAM, located at the front of a WFS, serves as an anti-aliasing filter providing accurate and stable measurements. Among the WFS concepts, the spatially filtered Shack-Hartmann WFS (SF-SH-WFS) (Poyneer & Macintosh 2004) is the unique concept of passive filtering proposed until now, which consists in using a pinhole at the front of the sensor. However, it is a non-linear filter which generates spurious low spatial frequencies, contrary to DAM which is a priori linear and may exceed the performance of its precursor. DAM upstream of a Shack-Hartmann WFS (DAM-SH-WFS) is free of aliasing. In addition, it reduces the spot distortion and improves the centroid computation. DAM upstream of a Pyramid WFS (Ragazzoni et al. 1996) (DAM-PYR-WFS) cancels out the aliasing as well, even if it is not so strong in the Pyramid WFS wrt Shack-Hartmann WFS. However, the Pyramid WFS shows more phase residuals at the high spatial frequencies, whereas the SF-SH-WFS is more sensitive to low frequencies (Verinaud 2005). Significant noise propagation remains at the highest frequencies closed to the WFS cutoff frequency (function of the number of lenslet of the WFS). In this domain, DAM may help to reach the highest sensitivity of a Pyramid WFS thanks to its high spatial frequency filtering properties. Finally, the anti-aliasing DAM filter is efficient and easy to operate with any wavefront sensor (DAM-SH-WFS, DAM-PYR-WFS, etc.).

9907-107, Session PSTh

SPIDER: a chip-scale interferometric imaging sensor

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The Lockheed Martin Advanced Technology Center is collaborating with the University of California, Davis to develop an ultra-thin optical imaging sensor called SPIDER (Segmented Planar Imaging Detector for Electro-optical Reconnaissance). SPIDER combines interferometric imaging concepts with photonic integrated circuit (PIC) technology to enable an electro-optic sensor with orders of magnitude reduction in size, weight, and power compared to an imager based on a conventional telescope design.

SPIDER consists of many photonic integrated circuit cards arranged azimuthally in a ring design, like spokes on a wheel. SPIDER images the object in the Fourier domain and reconstructs the image computationally. Lenslet arrays focus light from the scene into the waveguides on the photonic integrated circuits. Light from different pairs of lenslets are routed on the PICs via waveguides and combined interferometrically on the chip to produce fringes. By forming many lenslet pair combinations with varying lenslet spacing, a variety of interferometer baselines are created. The spatial frequency information of the scene is captured by measuring the phase and amplitude of the interference fringes of each baseline. An image is formed computationally by reconstructing the intensity distribution from the spatial frequency information via a 2D Fourier Transform through the van Cittert-Zernike theorem.

A high-resolution image can be formed in a small amount of time as the thousands of channels containing the spatial frequency information can be sampled simultaneously. Compared to the complex, mechanical delay lines required by many direct detect imaging interferometers, the interferometer path lengths in the photonic integrated circuits can be matched to micron precision and thus no scanning is required to form the interference fringes. SPIDER is inherently a multi-spectral device—light received at each lenslet

is spectrally demultiplexed on the chip and interfered with light received by a different lenslet in the same spectral bin. This spectral demultiplexing allows the Fourier domain u-v plane to be filled in more efficiently using multiple spectral bins from the same lenslet pair.

Under the DARPA-funded SeeMe program in 2014, we fabricated a four channel (two baseline) photonic integrated circuit on silica and demonstrated the spectral splitting and interferometric beam combination measurement concepts. Under current DARPA funding for the SPIDER Zoom program, we are fabricating a complete chip (one spoke of the wheel) with 12 baselines and hundreds of waveguides using silicon nitride. We are testing this new PIC in our laboratory test bed built specifically for this task.

In this talk we will give a brief summary of previous work, provide an overview of the test bed and scene generator, and present the first imaging results obtained with this experiment to validate the measurement concept. Comparison with the expected performance and other designs trades also will be discussed.

[1] A. Duncan et al., "SPIDER: Next Generation Chip Scale Imaging Sensor," Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference (2015). ?

[2] S. T. Thurman et al., "System Design for a SPIDER Imager," Frontiers in Optics 2015, OSA Technical Digest, paper FM3E.3 (2015).

9907-108, Session PSTh

Ultrafast laser inscribed waveguides for mid-infrared interferometry

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The direct detection of exoplanets is one of the major goals of astrophysics in the next couple of decades. The black-body radiation of a cool stellar object like a planet sits in the mid-infrared, between 2.0 and 12.0 ?m. Moreover, the contrast between a M-class star and the orbiting planet around it becomes most favorable in the astrononomical L-band (3.5 - 4.1 ?m) by many orders of magnitude. This makes the L-band the most promising wavelength for nulling interferometry.

Dragonfly is a pupil remapper interferometer aiming to provide a fully integrated photonic solution for direct imaging astrophysical targets through the turbulent atmosphere. This instrument has already been successfully demonstrated in the NIR and now we are translating this platform to the MIR. The core of this instrument is an integrated photonic device fabricated using the ultrafast laser inscription technique, where a femtosecond laser is tightly focused inside a transparent material (usually glass or crystal).

With the femtosecond laser direct-write technique we can induce, by cause of nonlinear processes, a permanent refractive index change within the focal volume. The glass/crystal sample is placed on a XYZ translation stage, allowing for the fabrication of highly repeatable full-3D photonic microstructures inside the material. The femtosecond laser direct-writing has already been demonstrated as a viable solution for 3D integrated photonics for astronomy.

The main restriction for an efficient photonic stellar interferometer is to have low-loss waveguides (usually <1 dB/cm losses). Therefore, we will present a comprehensive study of materials compatible with the direct-write technique and that are transparent in the mid-infrared. The materials range from commercial to custom-engineered chalcogenide and fluoride glasses. These waveguides were fabricated using two laser systems with repetition rates between 1 kHz and 5.1 MHz and pulse durations between ~50 fs and ~1.5 ps. The characterization and single-mode transmission properties of the waveguides in the mid-IR was done free-space coupling the light of a 3.4 ?m HeNe laser.

9907-109, Session PSTh

Using chalcogenide architecture for mid-IR photonic on-chip nulling interferometers

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Direct imaging of exoplanets, where a planet is separately resolved at the image plane, promises to provide critical answers to questions of planetary evolution and formation. New photonic technologies have enabled light to be precisely channelled; delayed; and interfered, all on a monolithic chip: facilitating a new generation of interferometric instrumentation for astronomy. To date, the materials used to create photonic chips have focused on interferometers in the visible and near-IR wavelengths. However; the contrast ratio between the planets and host star becomes favourable in the Mid-IR wavelengths, beyond ~3.5um. Hence, new materials are required to extend the reach of photonics into this regime.

To enable high contrast detection for the next-generation photonic interferometers we present a laboratory characterization of an on-chip Bracewell nulling interferometer prototype, operating at a wavelength of 4um. This chipset was lithographically fabricated using a mid-IR transparent glass – Chalcogenide. The low loss of this glass, already established to be 0.3 dB/cm, makes the nuller similar in performance and architecture to existing chips used in instruments like GRAVITY, PIONEER and Dragonfly, but with the added ability to operate upwards of 10 um in wavelength.

Using this novel approach to MIR fabrication we present a beam combiner using Multimode-Interference couplers (MMIs) that operate over a broader wavelength range and more robust in terms of fabrication tolerances– as opposed to modified evanescent field couplers that are typically used. The nuller itself is made of cascaded MMIs, taking 4 input channels and creating both a null output, between two input pairs, and a photometric tap. The resulting nulled ports are routed to a second tier MMI that can recover the fringes, or provide a second null, with the bright port used for calibration.

This new approach to fabricating MIR photonic devices, specifically nulling interferometers, will provide astronomers with another option when

implementing the next generation of astronomical photonics in the mid-IR wavelengths.

[2] A. Saviauk et al., Appl. Opt. 52, 4556 (2013).

[3] S. Minardi, Phys. Rev. A 92, 013804 (2015).

[4] S. Lacour, et al. Proc. SPIE 7013, 16 (2008).

9907-110, Session PSTh

All-in-one 4-telescope beam combination with a zig-zag array of waveguides

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Multi-telescope beam combination with integrated optics (IO) bear several advantages over bulk optics instruments, such as miniaturized packaging, considerable reduction of alignment procedures and stable interferometric transfer function. To date, IO beam combiners have been mainly manufactured for near-infrared wavelengths, exploiting the maturity of silica-based photolithographic technologies.

The desirable extension of the operation bandwidth of IO beam combiners to mid-infrared (MIR) wavelengths has been so far been prevented by the low maturity level of IO manufacturing technologies for MIR-transparent materials.

A very promising avenue for IO manufacturing at MIR wavelengths is ultrafast laser inscription in chalcogenide glasses. Additionally to being suitable for the processing of a large variety of substrate materials, this technique offers three-dimensional (3D) structuring capabilities. The latter feature is very interesting because it permits the simplification of the IO beam combiner design, e.g. by removing the need for waveguide crossings in pair-wise beam-combiners [1]. Further, the 3D geometry allows the simplification of the beam combiner down to a regular array of straight waveguides arranged on a square lattice (the so called discrete beam combiners or DBC [2,3]).

In the context of the DBC we have recently achieved a major breakthrough by designing a 4-telescopes, all-in-one beam combiner designed for a central wavelength of 3.4 microns.

The beam combiner features an array of 23 evanescently coupled waveguides arranged on a zig-zag lattice. The array configuration allows the dispersion of light in one dimension without the limits imposed by the previously investigated square array geometry [2,3]. This enables the use of DBC in high-resolution spectral interferometric instruments. Notice that a fully linear array of waveguides cannot be used as an interferometric beam combiner due to the absence of second order coupling between the waveguides [4], thus making the zig-zag geometry the only beam-combining waveguide array compatible with high-dispersion spectro-interferometry. The design of the array has been optimized to ensure a well conditioned V2PM transfer matrix (condition number 3.8), which is similar to that of the 4-telescope IO beam combiner of PIONIER (condition number 3.6, [5]).

Additionally, we have manufactured several samples of the array by direct laser writing in Gallium Lanthanum Sulfide glass, a highly transmissive material in the mid-infrared. The single waveguides were written by means of a laser multi-pass procedure which enables the precise tailoring of the waveguide core cross-section geometry. Writing parameters were optimized to achieve nearly circular mode fields.

Initial near-field characterization of the fabricated samples at a wavelength of 3.4 microns are encouraging, but require a better control of the polarization dispersion of the single waveguides and a significant suppression of stray light originating from poor coupling efficiency at the input waveguides.

Work is currently in progress to improve the manufacturing parameters and characterize experimentally the the V2PM matrix of the beam combiner.

[1] A. Rodenas, et al. Opt. Lett. 39, 392 (2012).

[2] S. Minardi, T. Pertsch, Opt. Lett. 35, 3009 (2010).

9907-111, Session PSTh

ALOHA @3.39μm: implementation of the up-conversion interferometer in the L band

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In the general framework of thermal infrared astronomical imaging, the mid infrared (MIR) domain addresses several prominent scientific areas like protoplanetary disc, brown dwarf or nebula studies. A few instruments such as Matisse, Visir or Midi, are able to provide data in the L, M and N band working with very low flux. In all these instruments, each interferometric arm can involve more than twenty mirrors. At room temperature, the thermal radiation of the mirror train can easily exceed the astronomical signal, significantly reducing the limiting magnitude to be observed. The related current experimental configuration requires the use of a chopped and nodded detection modes and their related data processing to enhance the Signal to Noise Ratio.

In order to limit the impact of this predominant noise contribution, the ALOHA (Astronomical Light Optical Hybrid Analysis) instrument promotes a hybrid interferometer concept where the astronomical light is frequency shifted into the near infrared domain through a sum frequency generation process. The MIR signal has to be converted out of the thermal infrared domain as close as possible to the telescope focus. This way, the main part of the instrumental chain would not be subject to any thermal noise disturbance.

A previous work among our team, led by P. Darré (ALOHA/CHARA at 1.5μm: sensitivity improvement and on-sky ability to detect astronomical sources in H band), has also investigated the joint use of sum frequency generation (SFG) and high resolution imaging by spatial coherence analysis at 1550 nm down to the photon counting regime. This work is performed in order to extend performances of ALOHA from the H band to the L band. Our inlab setup is conducted with a 3.39μm HeNe laser as a signal source. In each interferometric arm, the optical field is converted in a periodically polled niobate lithum (PPLN crystals) powered by a 1.06μm pump to generate a converted signal at 810nm. The shifted signal is injected in a single-mode fiber. Our converted signals from each arm of the interferometer are mixed by a fibre coupler. All our guided components are single-mode and polarisation maintaining. As a consequence we control the spatial overlapping, performing the spatial filtering problems. One can notice these elements have very low losses, opening the field of hectometric to kilometric interferometers.

A preliminary experiment has been conducted in the high flux regime (3mW signal power) and confirms the possibility to use a non linear stage on each arm of an interferometer dedicated to high resolution imaging in the L band. We aquired fringes with an average contrast of 98±2% over 1500 measurements.

We got a very high fringe contrast thanks to the use of polarisation maintaining single mode fibres. This first step validates our setup experimental calibration. Our current investigations are focused on the photon counting regime by attenuating the input signal monochromatic flux and addressing faint broadband sources to fit the astronomical requirements.

9907-112, Session PSTh

6- and 8-telescope discrete beam combiners

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Imaging optical interferometry requires the evaluation of the complex visibilities over a large number of baselines. Current facilities can handle the combination of up to 6-telescopes but planned and future interferometric facilities (such as the MROI [1] or the Planet Formation Imager [2]) could require the combination of up to 20 telescopes.

While an all-in-one combiner for such a large number of telescopes may be impractical due to sensitivity and construction issues, a web of instruments combining partially redundant sub-sets of the telescope array could improve sensitivity at the expense of delivering visibilities over a smaller number of baselines.

Candidate devices for the single beam combination units are integrated optics (IO) circuits which can deliver highly stable transfer functions, miniaturization and simple maintenance procedures.

In this context, we evaluated the optimal waveguide configuration for the beam combination of 6 telescopes by means of an IO discrete beam combiner (DBC), that is a regular array of evanescently coupled waveguides disposed at the nodes of a two dimensional lattice [3].

Advantages of the DBC are potentially the minimal number of pixels per spectral channel required to reconstruct the whole coherence information of the telescope array, and the simplicity of the construction of the combiner, which allows a straightforward scaling of the device to a large number of telescopes.

Here we propose the use of a new figure-of-merit (FoM) for the theoretical evaluation of the performance of a multi-telescope all-in-one beam combiner, namely the condition number (CN) of the visibility to pixel matrix (V2PM [4]) by the square root of the number of output channels of the combiner. We show that by definition this FoM is proportional to the maximal relative error of the quadratures of the retrieved visibilities.

To evaluate the expected V2PM, we modeled the DBC in the frame of the coupled mode approximation of a rectangular lattice of waveguides. The model assumes that the modes of each waveguide of the array are only slightly perturbed by the neighboring waveguides. The model includes the first order coupling between waveguides (in the horizontal and vertical direction) and the second order coupling (in the diagonal direction). The existence of the diagonal coupling has been recently found to be a necessary condition for the retrieval of the complex visibilities from the output excitation pattern of the array [5].

We found that the chosen figure of merit calculated as a function of the number of waveguides has a flat minimum corresponding to about 50 waveguides, equivalent to a 7x7 array. As a further optimization procedure, we studied the impact of the diagonal coupling strength of a 7x7 array of waveguides. Numerical simulations show that for a diagonal coupling strength larger than 10% of the vertical/horizontal one, the FoM remains basically constant.

We further report on the possible input waveguide configuration of an 8-telescope combiner featuring 8x8 or 9x9 waveguides.

[1] D.F. Buscher et al. J. of Astron. Instrum. 2, 1340001 (2013)

[2] J. D. Monnier et al. Proc. SPIE 9146, 914610 (2014).

[3] S. Minardi, T. Pertsch, Opt. Lett. 35, 3009 (2010).

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[5] S. Minardi, Phys. Rev. A 92, 013804 (2015).

9907-113, Session PSTh

Model-based calculations of fiber output fields for fiber-based spectroscopy

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The accurate characterization of the field at the output of optical fibers is of relevance for precision spectroscopy in Astronomy. The modal effects in the far field angular distribution of the fiber translate to the illumination of the pupil in the spectrograph and impact on the resulting point spread function (PSF).

A model is presented that is based on the Eigenmode Expansion Method that calculates the output field from a given fiber for different manipulations of the input field. Results are shown for different configuration parameters, such as: spatial and angular displacements of the input field, spot size variations, propagation length, different transverse fiber geometries and different wavelengths.

This work is in context with the phase A study of the fibre-system for MOSAIC, a proposed multi-object spectrograph for the European-Extremely Large Telescope (E-ELT-MOS).

9907-114, Session PSTh

Use of a photonic lantern into a fiber beam combiner

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We investigate the use of photonic lanterns in a fibre beam-combiner. One of the problems of fibre combiners is that the single-mode fibres coupling is affected by the atmospheric seeing. This effect could be potentially mitigated using a "photonic lantern". A photonic lantern converts the multi-mode input at the focal plane of a telescope to N single mode outputs. In presence of atmospheric seeing the light of the telescope will couple with one or more of the single-mode outputs unlike the current interferometers where coupling can be sporadic in bad seeing conditions. In a stellar interferometer each telescope focal plane could be coupled with a photonic lantern. After beam combination each single-mode outputs of the lantern will interfere with all the others. N single mode outputs from each lantern will make N non independent closure phases that can be averaged. Using this method the noise on the closure phase on independent baseline triangles could in principle be reduced by the square root of N.

9907-115, Session PSTh

Fringe tracking at longer wavelengths using near- and mid-IR integrated optics devices

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The availability of a reliable fringe tracking system is essential for optimal operation of a stellar interferometer to access fainter objects through long integration time. A typical fringe tracker compensates for the differential optical path differences (OPDs) due to the turbulent atmosphere and instrumental vibrations through additional delay lines. The influence of atmospheric turbulence and instrumental vibrations are weaker at longer wavelengths than the shorter wavelengths. On the other hand, ground based observations at longer wavelengths suffer from higher thermal background. Despite this, fringe tracking in the L-band could be advantageous when observing young stellar objects which emit more radiation at longer wavelengths in the infrared.

In this paper we investigate the possibilities to perform fringe tracking in the K and L bands at VLTi taking advantage of integrated optics beam combiner based on near and mid-infrared transparent GLS Chalcogenide glass. For this Purpose, we developed an atmospheric OPD simulator based on Von Karman turbulence statistics including the instrumental vibrations measured at the VLTi. We analyze the efficiency in performing group and phase delay tracking in the L band and address the case of dual-band fringe tracking by measuring the broadband fringes in K and L bands simultaneously. The general objectives are to estimate L-band fringe tracking sensitivity limit and check if the K+L group delay tracking associated to a "Blind mode" for the estimations of the science visibility and phase could be more sensitive than conventional K-band only phase+group delay fringe tracking.

9907-116, Session PSTh

Near-IR active beam-combiner for multi-telescope spectro-interferometry based on surface waveguide gratings and lithium niobate waveguides

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Integrated optics spectro-interferometers, thanks their compacity and robustness, are well adapted for reducing size and weight of spatial spectrometers. One of the main type of integrated optics spectrometers is based on the dispersed mode. Following the principle of Grating Waveguide Structures, we extract the optical signal from a channel waveguide using a diffraction grating, made by Focused Ion Beam, that records nano-grooves periodically along the waveguide. Then an optical relay allows us to obtain the wavelength spectrum on the Fourier plane of a first cylindrical lens, two others cylindrical lens permit to get an achromatic system.

Using this approach, we have developed a 3T and 4T spectro-interferometer than can be used to combine and spectrally study signal coming from several telescopes. Indeed it's possible to extract the signal of two close waveguides and defocus the first cylindrical lens. This allows to get a wide area on the detector and in the area of overlapping of this two (or multiple) spots the light coming from the two (or multiple) waveguides will generate interference fringes.

The waveguides are realised using X-cut, Y-propagating Lithium Niobate. This allows us to get a strong angular separation of the TE and TM diffracted modes (due to the different effective index of the two modes), and using the electro-optic properties we are able to integrate a delay line in our chip by adding electrodes near the waveguides. We can thus scan and center the zero-optical path delay between the different entries and obtain in the detector the non-redundant fringes as a function of wavelength. This permit us to get a very compact system (the chips is 4cm long).

The device allows to obtain non-redundant interference fringes up to 4 Telescopes by extracting light from channel waveguides using surface gratings, which spectrally disperse the signal. The interference pattern is obtained on the detector by overlapping the light extracted from above the waveguide using a cylindrical relay optics. The whole system is contained in a volume <1L.

We will present the 3T and 4T results of our system, in the near IR (centered at 1.55um): grating extraction efficiency, spectral domain and resolution trade-off, related to the detector characteristics.

9907-117, Session PSTh

Novel multi-telescope beam combiners for next generation instruments (FIRST/SUBARU)

Guillermo Martin, Institut de Planétologie et d'Astrophysique de Grenoble (France); Florent Gardillou, Cedric Cassagnettes, Denis Barbier, Teem Photonics S.A. (France); Clement Guyot, Jérôme Hauden, iXBlue SAS (France); Elsa Huby, Univ. de Liège (France); Sylvestre Lacour, Observatoire de Paris (France) and Lab. d'Etudes Spatiales et d'Instrumentation en Astrophysique (France)

Integrated optic devices are nowadays achieving extremely good performances in the field of astronomical interferometry, as shown by PIONIER or GRAVITY silica/silicon-based instruments, already installed at VLTI. In order to address other wavelengths, increase the number of apertures to be combined and eventually ensure on-chip phase modulation, we are working on a novel generation of beam combiners, based on the hybridization of glass waveguides, that can ensure very sharp bend radius, high confinement and low propagation losses, together with lithium niobate phase modulators and channel waveguides that can achieve on-chip, fast (>100kHz) phase modulation. The work presented here has been realized in collaboration with our technological partners TeemPhotonics for glass waveguides and iXBlue-PSD for lithium niobate phase modulators. We will present our results on a hybrid glass/niobate (passive/active) beam combiner, that has been developed in the context of FIRST/SUBARU 9T beam combiner (See Huby et al.). The combiner is structured in three parts: a) the first stage (passive glass) achieves beam splitting from one input to eight outputs, and that for nine input fibers coming from the sub-apertures of the Subaru telescope ; b) the second stage consists on a 72 channel waveguides lithium niobate phase modulator in a push-pull configuration that allows to modify on-chip the relative phase between the 36 pairs of waveguides ; c) a final recombination system of Y-junctions (passive glass) that allows to obtain combination of each input to every other one. The aim of this presentation is to discuss different issues of the combiners, such as transmission, birefringence, half-wave voltage modulation and spectral range.

9907-118, Session PSTh

Recent results on photonic devices made by laser writing: 3D 3T near IR waveguides, mid-IR spectrometers, and electro-optic beam combiners

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Direct laser writing is a powerful technique for the development of astrophotonic devices, namely by allowing 3D structuring of waveguides and structures. One of the main interests is the possibility to avoid in-plane crossings of waveguides, that can induce losses and crosstalk in future multi-telescope beam combiners. We will present our results in 3D three

telescope beam combiners in the near infrared, that allow for phase closure studies. Besides, laser writing can be used to inscribe a grating over long distances along the waveguide direction. This can be used as an on-chip diffraction grating or as a way to sample a stationary wave that can be obtained in the waveguide. Thus, integrated optics spectrometers based on the SWIFTS concept (stationary wave integrated Fourier transform spectrometer) have been realized and characterized in the mid infrared using commercial chalcogenide glasses. Finally, we will also present our results on laser writing on electro-optic materials, that allow to obtain waveguides and beam combiners that can be phase-modulated using electrodes. We have focused our work on two well known materials: Lithium Niobate, that allows for TM waveguides and has a high electro-optical coefficient, and BGO, that has a lower coefficient, but presents the advantage of being isotropic, guiding both TE & TM polarizations identically.

9907-119, Session PSTh

An integrated-optic single-mode photonic nuller: development and on-sky testing

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Ultra-high angular resolution, high-contrast imaging is crucial to many key areas of astronomy, including direct imaging of exoplanets and protoplanetary disks. However achieving high-contrast observations at or beyond the telescope diffraction-limit from ground-based telescopes - even with advanced AO systems - is extremely challenging. Pupil-segmenting interferometry and coronagraphy both have their limitations. Coronagraphy is limited by the inner-working angle of the device, and while interferometry has no strict inner-working angle it struggles to reach the needed contrasts due to mixing of the faint planet/disk light with the bright starlight.

Nulling interferometry addresses both these problems. Like a conventional interferometer it can perform super-diffraction limited imaging, but like a coronagraph it rejects the unwanted starlight in favour of the fainter science signal (from the disk or planet). This is achieved by destructively interfering the starlight with itself. Conventional nulling interferometry is an established technique, but a new generation of photonic nullers is poised to revolutionise the field.

Here we present a photonic nulling interferometer based upon an integrated photonic device manufactured using ultrafast laser inscription. Two sub-apertures on opposite sides of the telescope pupil are optimally injected - via steerable segments of a MEMS segmented deformable mirror and microlens array - into two single-mode waveguides of the photonic device. Each waveguide first encounters a Y-splitter inscribed within the chip, which splits off some of the light for simultaneous photometric measurements. The majority of the light continues to propagate along two (path-length matched) waveguides, which are then interfered via a (directly inscribed) evanescent coupler. The two outputs of the coupler are then routed to the output face. These four outputs are butt-coupled into single-mode fibres and sent to sensitive photodetectors.

By adding a pi phase shift to one input waveguide (via the MEMS mirror), destructive interference takes place in the coupler, and the null appears at one output waveguide (and the constructive interference at the other). By measuring the null depth and the coupling efficiency (using the photometric channels) as a function of time, the astrophysical null can be determined via a statistical analysis, revealing spatial information on the astrophysical object.

Performing nulling using a single mode fibre or waveguide offers greatly improved precision over bulk optics due to their spatial filtering properties. The instrument described here offers further advantages over optical-fibre based designs. It offers increased stability over bulk fibres, with critically optical-path-length matched routes taking place within waveguides inscribed within a solid glass chip. Photonic Y-splitters allow photometric measurements to be made simultaneously with the null measurements, avoiding the time-lag between null and photometry experienced when using a chopper wheel. Both the nulled (destructive) and the bright (constructive) channels are measured, providing extra data to constrain the astrophysical null. Critically, this design is easily scalable, with multiple nulling channels - and subsequent recombination to perform closure-phase nulling - able to all be fabricated in a single photonic chip.

Here, we will describe the instrument and present the results of laboratory characterisation and on-sky tests made at the 3.9m Anglo-Australian Telescope.

9907-120, Session PSTh

Interferometric field-of-view measurements at the VLTI

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In August 2014 we performed technical observations at the VLTI with the AMBER and PIONIER beam combiners to measure the interferometric field of view (FOV). As targets we included binaries with component separations between 100 and 300 mas, for which orbits and/or interferometric speckle measurements are available from the Washington Double Star databases or from the literature. The analysis included effects such as bandwidth and time smearing of the interferograms, and photometric attenuation due to the seeing and image quality based on a new formalism of the ESO Exposure Time Calculators. We also consulted the literature for results of interferometric surveys such as the SMASH survey by H. Sana et al. 2014 to estimate the effective FOV for these instruments. Based on our analysis, we conclude that emission outside a FOV diameter of 160 mas will be significantly supressed if not completely invisible. These results provide important information as to the size of the source structure to be included when modeling interferometric data obtained with these instruments.

9907-121, Session PSTh

High-spectral resolution for all! Recovering full spectral 3D images from observations at uniform correlated magnitude

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Sensitivity is one of the major issue of optical interferometry as it prevents interferometers access to a broader community (eg: AGN, exoplanets…). This prevents the observation not only of faint targets but also of well resolved object (like giant stars) star with large baselines. This curse plagues many objects as bright enough targets are often well resolved.

It is a major challenge especially for any future interferometer with long baselines like PFI.

Reducing the spectral dispersion is a way to mitigate the problem by increasing the number of incident photons per pixels. Unfortunately, this is at the cost of a precious astrophysical spectral information. Furthermore, inside such broad spectral channels, the variation of flux ratio between structures (e.g. star, shell…) implies a strong chromatic effect in the visibilities that may forbid astrophysical interpretations (Kluska, 2014). To address this problem, we propose a new observation mode for interferometric imaging: varying the spectral resolution with the baseline in order to keep similar fringe SNR whatever are the object visibilities and then making image reconstruction at the full spectral resolution using adapted priors.

In the present work, we demonstrate that it is not necessary to make all measurements with same spectral dispersion to recover image at the full spectral resolution. In this observation mode, the low frequencies are measured at full spectral resolution whereas the high frequencies are measured on broader bands. The estimation of the missing high frequency spectral information is done by the image reconstruction algorithm using regularization functions enforcing adapted spatio-spectral priors. These regularization tend to correlate high frequencies across the bandwidth. This is justified by the fact that, in most cases, spatial variations of spectrum are correlated with a variation of surface brightness in a broader band. As a consequence, a precise estimation of high spatial frequencies in broadband can be used as priors to determine high frequencies in each spectral channel.

Such joint reconstructions are already done in other fields (color imaging, remote sensing, microscopy,…) and we are convinced this will give the possibility to use large baselines even for well resolved objects and will be a step toward future kilometer long baselines interferometers like PFI.

9907-122, Session PSTh

Effective a posteriori co-phasing of interferometric fringe data

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We have recently shown that a posteriori co-phasing of multi-spectral interferograms was possible (Soulez et al., 2014). In this contribution, we develop the means to extend our approach so that it can be applied to actual data as provided by AMBER or MATISSE instruments. The main advantage of the proposed post-processing technique is that it requires no modifications of the instruments and yield interferometric observables with higher SNR and much fewer unknowns (in particular for the Fourier phase) than conventional measurements. In order to perform the co-phasing of a complete sequence of interferograms, we jointly estimate a global phase template and the frame dependent optical path errors due to the turbulence.

While the chromatic aspect of the analysis (or data) helps to fit the chromatic turbulence phase shift model, the adaptive behavior of the template update allow to recover the phase up to the initial reference.

We show that this strategy is effective for very low SNR data. After this initial co-phasing stage, we derive the amplitude and the phase of a chromatic complex visibility accounting for all the photometric and interferometric frames of a sequence. This complex visibility is the maximum likelihood estimator of the uncalibrated complex visibility of the object up to a low rank phase aberration and carries more information than conventional interferometric observables. We assess the effectiveness of our method on simulated and actual AMBER data. We also compare the lowest SNR that can be achieved to the theoretical bounds and estimate the gain in sensitivity compared to usual interferometric data.

9907-123, Session PSTh

Real-time piston variation reconstruction with wavefront sensor data

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Atmospheric piston variation as observed by AO: The scientific goal is to increase the sensitivity of an adaptive optics (AO) supported optical interferometer (like the VLTI) to observe larger, statistically relevant samples of rare objects, like massive young stars, and AGN as well as to reach new target classes like brown dwarfs and microquasars, currently out of reach for optical interferometry. To do so, we propose to increase the sensitivity by deriving the time-variable atmospheric piston drift from AO-data, and therefore increasing the coherence time by up to two orders of magnitude over the currently implemented approach of direct fringe tracking. This in turn allows for much longer coherent integration times on the beamcombining camera. This new approach uses the time series of AO wavefront information to reconstruct the atmospheric piston variation.

The core of the algorithm derives the dominating wind speed and direction, using the frozen atmosphere approximation, and has been demonstrated to work with multi?layer atmospheric simulations. Combining wind and atmospheric tilt information then gives the piston drift. A key advantage is that no additional hardware is needed, if the interferometer is already equipped with a piston?neutral AO system and with fast delay line fringe tracker actuators as is the case for the VLTI. The initial goal is to apply the algorithm to MATISSE operation and to address GRAVITY in a second stage, since the longer operating wavelengths of MATISSE (3-10micron) pose lower requirements on the fringe tracking precision. Ideally this technique is combined with advanced accelerometer-based telescope vibration sensing (see contributions by M. Glück et al. and M. Böhm et al. to this SPIE), since telescope vibrations are the second dominant fringe motion disturbance, besides the atmosphere.

9907-124, Session PSTh

Image restoration for a hypertelescope

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In order to resolve exoplanets an effective aperture with several tens or more kilometers is needed. A hypertelescope consists of many elemental telescopes like an interferometric array. The beams from the elemental telescopes are enlarged and arranged compactly on the imaging lens to

form the snap-shot image. This procedure is referred to densification. This densification works to concentrate energy to form the image, otherwise the energy is distributed to periodically formed images. When quite a large number of elemental telescopes are available, a high-quality image is obtained. However, in practice, a limited number of elemental telescopes will be employed for the sake of the cost reduction. In this respect non-redundant arrays are preferable.

Snap-shot images formed with a limited number of elemental telescopes, however, do not exhibit high quality features, because the spatial frequency sampling is not dense enough to image properly exoplanets. Some image restoration should be implemented to reveal the surface structures of exoplanets.

A non-redundant array with 20 telescopes is postulated as a model of hypertelescope and an image of Jupitar as an object in our computer simulation. The pupil densification is conducted as a full spectrum densification (FSD) mode (Aime et al. (2012) A&A 543, A42). It is supposed that the object cannot be resolved with each elemental telescope. One of annoying problems in hypertelescope image restoration is shift-variant characteristic of PSF that is caused by the pupil densification. The CLEAN algorithm manages to restore images formed with shift-variant PSF. On the other hand pre-processing to a raw image can transform the shift-variant characteristic into the shift-invariant one. In such a case we can employ commonly used Wiener filtering and Richardson-Lucy algorithm.

We evaluate the quality of a restored image with root-mean-square-error (RMSE) . The CLEAN algorithm works well for the noise-less image. For noisy images the pseudo

Wiener filtering seems to restore better the pre-processed ones. We show the image restoration results and the effectiveness of the image restoration.

9907-125, Session PSTh

Rotation and translation registration of bandlimited interferometric images using a chirp z-transform

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Sparse aperture, interferometric imaging techniques often rely on rotations of the interferometer (or the object) in order to sufficiently sample the spatial frequencies of the object such that an artifact-free image of the source can be computed from the measurements. For the case of spatio-spectral imaging interferometry, image reconstruction algorithms require that all rotations and translations are known well enough to register the measured low-resolution images to within the resolution of the desired high-resolution image to be recovered. Despite measurements of the rotation angles between the source and the interferometer, experimental effects, including image motion from temperature fluctuations, will prevent precise knowledge of the registration parameters, including image translations between measurements and errors in rotation angles. Other factors associated with an experimental testbed, such as NASA's wide-field imaging interferometry testbed (WIIT), cause the image on the detector to shift as a function of the interferometer's baseline length. In order to obtain precise estimates of the registration parameters without prior information of objects within the field-of-view, the image rotation must be simulated accurately. Because the measured images are bandlimited by the interferometer's imaging system, Fourier-domain image rotation algorithms can be applied to the images without introducing aliasing artifacts. As a result, a chirp z-transform can be applied to the image to simultaneously perform arbitrary rotation, translation, and down-sampling. We combine the chirp z-transform and nonlinear optimization to create an image registration algorithm, incorporating a multi-step procedure to improve the accuracy of the retrieved registration parameters. Included is the result of image registration of simulated images that are representative of scenes measured by WIIT. This image registration procedure will ultimately improve the high-resolution hyperspectral output of image synthesis algorithms for wide-field interferometric imaging.

9907-126, Session PSTh

Image reconstruction method IRBis for optical/infrared long-baseline interferometry

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We will present IRBis, an image reconstruction method for optical/infrared long-baseline interferometry. IRBis is part of the MATISSE pipeline. IRBis can reconstruct images from a) measured visibilities and closure phases, or from b) measured complex visibilities (i.e. the Fourier phases and visibilities). The applied optimization routine ASA_CG is based on conjugate gradients. The method allows the user to implement different regularizers, as for example, maximum entropy, smoothness, total variation, etc., and apply residual ratios as an additional metric for goodness-of-fit. In addition, IRBis allows the user to change the following reconstruction parameters: (a) FOV of the area to be reconstructed, (b) the size of the pixel-grid used, (c) size of a binary mask in image space allowing reconstructed intensities > 0 within the binary mask only, (d) the strength of the regularization, etc.. The two main reconstruction parameters are the size of the binary mask in image space (c) and the strength of the regularization (d). Several values of these two parameters are tested within the algorithm. The quality of the different reconstructions obtained is roughly estimated by evaluation of the differences between the measured data and the reconstructed image (using the reduced chi^2 values and the residual ratios). The best-quality reconstruction and a few reconstructions sorted according to their quality are provided to the user as resulting reconstructions. We will describe the theory of IRBis and will present several applications to simulated interferometric data and data of real astronomical objects observed with the VLTI-AMBER instrument. We investigate, for example, image reconstruction of MATISSE target candidates by computer simulations. We have modeled gaps in a disk of a young stellar object and have simulated interferometric data (squared visibilities and closure phases) with a signal-to-noise ratio as expected for MATISSE observations. We have performed image reconstruction experiments with this model for different flux levels of the target and different amount of observing time, that is, with different uv coverages. As expected, the quality of the reconstructions clearly depends on the flux of the source and the completeness of the uv coverage. We will show also reconstructions obtained from observations of real astronomical targets. We will present reconstructions of the Luminous Blue Variable Eta Carinae obtained from AMBER observations in the high spectral resolution mode in the K band. We obtained diffraction-limited reconstructions of Eta Car in all spectral channels (~64 channels) of the high spectral resolution (R~12000) observation of the Brackett Gamma line.

9907-127, Session PSTh

High fidelity imaging of geosynchronous satellites with MROI

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Interferometry provides the only practicable way to image satellites in Geosynchronous Earth Orbit (GEO) with sub-meter spatial resolution.

The Magdalena Ridge Observatory Interferometer (MROI) is being funded by the US Air Force Research Laboratory to demonstrate the 9.5 magnitude sensitivity (at 2.2 micron wavelength) and baseline-bootstrapping capability that will be needed to realise a useful turn-key GEO imaging capability. This program will utilise the central three telescopes of the MROI and will aim to validate routine acquisition of fringe data on faint well-resolved targets.

In parallel with this effort, the University of Cambridge are investigating the spatial resolution and imaging fidelity that can be achieved with different numbers of array elements. We present preliminary simulations of snapshot GEO satellite imaging with 4-, 7-, and 10-telescope deployments of MROI, and show the improvements in the recovered image obtained by combining contemporaneous low-spatial frequency measurements from a filled aperture telescope with the MROI data.

Our results indicate that faithful imaging of the main satellite components can be obtained with as few as 7 unit telescopes, and that increasing the number of telescopes to 10 improves the effective spatial resolution from 0.75 metre to 0.5 metre and enables imaging of more complex targets.

9907-128, Session PSTh

Kernel phase and kernel amplitude in optical imaging

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Kernel phase interferometry is a technique for high angular resolution in Fizeau interferometry, extending the idea of closure phases to redundant pupils to obtain the high signal-to-noise needed to detect faint companions close to their host stars. I will discuss recent work demonstrating kernel phase from the ground with the P3K AO system on the Palomar Hale 200-Inch Telescope, producing results comparable to aperture masking. I will present a generalization of the idea of kernel phases to calibrating amplitude errors, including atmospheric scintillation, residual amplitude aberrations from advanced AO techniques, and differential throughput across the optical path. This is a stepping stone towards extending the theory of optical self-calibration to more advanced optical systems, potentially even including coronagraphs. I will also discuss simulations of kernel phase, kernel amplitude and their application to JWST and WFIRST-AFTA.

9907-129, Session PSTh

Interbands phase models for polychromatic image reconstruction in optical interferometry

Antony Schutz, André Ferrari, Observatoire de la Côte d'Azur (France) and Lab. J.L. Lagrange (France); Éric M. Thiébaut, Ctr. de Recherche Astronomique de Lyon (France); Férréol Soulez, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Martin Vannier, David Mary, Observatoire de la Côte d'Azur (France) and Lab. J.L. Lagrange (France)

Astronomical optical interferometers (OI) sample the Fourier transform of the intensity distribution of a source at the observation wavelength. Because of rapid atmospheric perturbations, the phases of the complex Fourier samples (visibilities) cannot be directly exploited, and instead linear relationships between the phases are used (phase closures and differential phases). Consequently, specific image reconstruction methods have been devised in the last few decades. Modern polychromatic OI instruments are now paving the way to multi-wavelength imaging. This paper presents a variation of a spatio-spectral ("3D") image reconstruction algorithm called PAINTER (Polychromatic opticAl INTErferometric Reconstruction software). In its later form, the algorithm is able to solve large scale problems. It relies on an iterative process, which alternates estimation of polychromatic images and of complex visibilities. The complex visibilities are not only estimated from squared moduli and closure phases, but also from differential phases, which help to better constrain the polychromatic reconstruction:

• the closure phases are estimated by the mean of three bases phases estimation which are "closed" at a given wavelength. As a results, a closure phases helps to constrain the phases estimation of three bases at a given wavelength.

• The differential phases, difference of phase between wavelength for a given base, helps to constrain the problem of phases estimation between wavelengths. ?The objective of this communication is to improve the phase estimation step taking into account more realistic constraint in the phases estimation process. ?In the first version of PAINTER, the differential phases are computed using a single reference per spectral channel. In this case, the differential phases corresponding to two distant spectral channels may be affected by the atmospheric turbulence.

We propose in this communication to define new turbulent independent differential phases. This is achieved using multiple phase references across all the bandwidth.

Two solutions are proposed and the condition numbers related to the inverse problem that needs to be solved are studied in both cases. The benefits of the proposed modifications are illustrated by image reconstruction results

9907-130, Session PSTh

A method to assess the quality of reconstructed interferometric images

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We present a method to assess the quality of restored interferometric images, in which we take into account the resolution of the interferometer prior to image comparison.

Three type of astronomical objects (stellar cluster, young stellar object and stellar photosphere) are mock observed with VLTI configurations, and their images are reconstructed using MiRA.

We consider the most common merit functions to quantify the quality of the images, including the interferometry imaging beauty function and the ALMA fidelity function.

The major difference for other methods is that the reference image is convolved with a Gaussian effective PSF before quality assessment with the aforementioned metrics. By taking into account the resolution of the interferometer, this method prevents wrong classifications of images when compared with each other.

Following the work by Gomes et al 2014, we use this methodology to infer in which conditions phase referencing and phase closure techniques yield similar restored images, when the observations are spanned during a fixed number of nights but using a different number of telescopes in each scenario. We demonstrate that when the (u, v)-space is judiciously chosen, phase referencing and phase closure techniques yield similar results.

9907-131, Session PSTh

Imaging methods for PFI

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Unlike the current generation of interferometers, the Planet Formation Imager (PFI) shall often work in a regime where a very large number of (u,v) points of relatively low SNR will be collected. Current image reconstruction codes are ill-adapted to such a reconstruction task. As the number of terms in likelihood is at least an order of magnitude larger than current data sets (especially if essential data correlations are taken into account), all software suffer from slow performance. Moreover, the reconstruction fidelity offered by conventional regularizers (e.g. total variation) also appears to be poor for typical PFI targets. We explore here possible solutions to both the likelihood and regularization issues.

9907-132, Session PSTh

User-friendly imaging algorithms for interferometry

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The scientific exploitation of the current and planned generations of interferometric instruments clearly depends on their imaging capabilities. Hardware developments such as combining more telescopes and developing phase referenced acquisition of the fringes will yield significant improvements. On the software side, many successful image reconstruction algorithms have been developed for optical/IR interferometry. However, successfully using these algorithms requires a high level of expertise, strongly restricting the number of potential users. OPTICON currently supports a Joint Research Activity (JRA) dedicated to providing easy to use image reconstruction algorithms for optical/IR interferometric data. The objectives of this JRA are to provide to the community a number of state-of-the-art image reconstruction methods with a common interface and with comprehensive documentation. We will present the tools developed by the JRA and make a demonstration of their usage. Our idea is to encourage users to consider image reconstruction as a data processing task. This implies that they will require the capability to compare the results of using different settings and algorithms in a consistent and unified way. The JRA has therefore designed a common framework for image reconstruction in order to unify the formats of the input and output data, and also the settings and control of the various algorithms. Exploiting this framework a common graphical user interface has been built. Currently BSMEM, MiRA and WISARD have been updated to use this framework and have been made available to the community. The proposed infrastructure is flexible and can accommodate the later addition of other existing and future imaging algorithms. The JRA is also providing tutorials and data samples to introduce the principles of image reconstruction and illustrate how to use the software products.

9907-134, Session PSTh

Cross verification of 450+ stellar calibrators observed with VLTI/PIONIER

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We have analysed 450+ stellar calibrators taken on several observing programs of VLTI/PIONIER. The goal of the present work is to identify calibrators with stellar companion and/or resolved flux which can bias the final calibrated visibilities. To do so, we used an iterative process using cross-calibration and the companion detection tool CANDID. We present the method and the first results. This work can be the basis of a verified database of calibrators for optical interferometry.

9907-135, Session PSTh

An interferometric view of binary stars

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Stars tend to form and live in binaries, with the fraction of binary stars being higher for more massive stars: the binary fraction increases from 25–30 % for M dwarfs and about 50% for solar-like stars, to more than 70% for B and O stars. Moreover, a significant fraction of these binary stars will interact in one way or another during their evolution. Mass transfer will affect the chemical composi?tion of the companion, which can for example become polluted in processed elements like in Algols or in Barium stars. It also leads to a mass increase of the companion, with sometimes strong consequences, such as blue straggler stars or Type Ia supernovae. Finally, mass transfer has also an impact of the evolution of the orbital separation. The study of binary stars is therefore critical to apprehend many of the most interesting classes of stars. Moreover, quite often, the study of stars in binary systems is our only mean to constrain stellar properties, such as masses and radii. Unfortunately, a great fraction of the most interesting binaries are so compact that they can be apprehended by high-resolution techniques only, and most recently by interferometry. I will present some results highlighting how interferometry is used in the study of binary stars, from finding companions and deriving orbits, determining the mass and radius of stars, to studying mass transfer in symbiotic stars, and tackling luminous blue variables. In particular, I will show how interferometric studies have allowed us to confirm a dichotomy within symbiotic stars, obtain masses of stars with a precision better than 1% and thereby serve as benchmark for future GAIA results, and help us find a new eta Carinae-like system. I will also illustrate the benefits for the study of binary stars one would get from upgrading the VLT Interferometer so as to be able to observe in the visible range.

9907-136, Session PSTh

Stellar physics in the mid-infrared with MATISSE

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We will present science projects that can be performed in the field of stellar physics with the MATISSE instrument. MATISSE is the second-generation mid-infrared instrument of the VLTI. MATISSE, with its milli-arcsecond resolution imaging capabilities, its spectral resolution of up to 5000, and the opening of the L and M bands (3.5-5.5 microns), will give access to unprecedented angular resolution spectro-interferometric-images of a variety of stellar objects. We will show detailed aperture-synthesis image reconstruction experiments performed with realistic

simulations of MATISSE data (e.g., uv coverage, target brightness, field-of-view) to illustrate the expected performance of MATISSE.

The strength of MATISSE is its capability to locate where the dust, molecular layers, and gas reside close to the stars. Studies of these regions are of great importance to improve our understanding of the mass-loss process, which is not yet well understood. Infrared spectro-interferometry provides a unique opportunity to probe the region in which mass outflows are initiated. The high spectral resolution mode will allow us to study the physics and kinematics of outflow regions with high spectral and high spatial resolution simultaneously (e.g., super-granulation, the kinematics of large-scale clouds in the atmosphere of supergiants, stellar winds from hot stars, wind collision regions in hot binaries). Examples of targets include Cepheids, AGB stars, red and blue supergiant stars, Luminous Variable stars, Be stars, and dusty Wolf-Rayet stars.

9907-137, Session PSTh

Model fitting of dusty pinwheel nebulae WR104: probing inner part with interferometry

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Wolf-Rayet stars are luminous massive blue star with strong and optically thick stellar wind. They are the immediate precursor of the supernovae type II. This strong wind exerts a major influence on their immediate surroundings, and play a dominant role in the evolution of their host galaxies. As a consequence, these stars show many lines of nitrogen and helium for WN stars and of carbon, oxygen and helium for WC stars. WC8 and WC9 exhibit a strong infrared excess triggered by hot and warm dust (Allen et al. 1972), produced by the central source while this is not the case in WN stars. These WR dust makers are few but remarkable in terms of the absolute dust-formation rate they exhibit. The wind-wind collisions in WR+O in such system offer ideal condition to reach critical densities to produce dust pattern observe around some Pinwheel nebulae (WR104, WR98a or WR118). The prototype star WR104 is the most studied pinwheel nebula to date (Tuthill et al. 2006). It was discovered as a "pinwheel" dusty nebula by Tuthill (1999) and subsequently observed in a follow-up series of observations (Tuthill et al. 2008), confirming its binarity and refining most of its parameters. These atypical dust shell are a remarquable problem for modeling and theory of dust production, some hydrodynamical and radiative transfer model was made to explain the Pinwheel pattern around the prototype WR104 (Harries et al. 2004; Lamberts et al. 2012). In lines of these studies, we used new interferometric data available in VLTI to study WR104 with the highest resolution. We used AMBER, the near-infrared focal instrument of the VLTI, which operates in the bands J, H, and, K (1.0 to 2.4 μm). AMBER can take profite of spectral information to probe an importante part of (u-v) plan. We will present the fitting software used which exploits a geometrical model of Pinwheel made of a succession of rings. We add an unresolved central point to explain increase of visibility observed in H band. This unresolved source could well be the central binary star. Furthermore, the AMBER data reveal that the pinwheel is diluted by diffuse emission in the system. The different model's parameters are difficult to constrain due to the relatively sparse (u-v) coverage available. Nevertheless, we developed different model and fitting method to interpret futur interferometry data. We present also the future possibilities of the next generation of interferometer MATISSE, curently developed in Nice, France. This new instrument will be able to observe in L and N band. For the first time, we will produce images in thermal infrared. Wolf-Rayet star and dusty producers are one of the scientific objective of this instrument.

9907-138, Session PSTh

Direct temperature map estimation in optical long baseline interferometry

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The arrival of 2nd generation beam combiners GRAVITY and MATISSE at the VLTI shed the light on the need of multispectral image reconstruction algorithm. Indeed, as they combine four telescopes with medium and high spectral resolution, it is now conceivable to use them as high spatial resolution integral field spectrograph by mean of image reconstruction. Image reconstruction is a very challenging problem. Recently, as part of the effort of the community to develop the research on multispectral image reconstruction the POLCA project gave birth to three methods : MiRA3D (Soulez et al, 2013), PAINTER (Schutz et al., 2014) and SPARCO (Kluska et al., 2014).

The reconstructed spatio-spectral data cubes give very valuable astrophysical information such as velocity, abundance or temperature map. It is important to notice that this astrophysical information represents often few estimated parameters per pixel (e.g. dispersion and mean velocity, temperature, relative abundance of few chemical elements,...) and lies only on a complex but small subspace (i.e. a manifold) of each spectra. Using this fact as priors to better contraint the reconstruction, our algorithm thus will provides directly a 2D map of parameters of astrophysical interest. Such an idea was already behind the principle SPARCO method that only estimates from polychromatic interferometric data a 2D image and a parametric model with different spectral index

In the presented work, we proposed the first method for reconstructing an objective temperature map from the interferometric polychromatic measurements. This approach is based on the MiRA3D algorithm in which we add the hypothesis that the spectrum of each pixel is described as a black body (or a combination of black bodies to take into account the variation of temperature within a pixel. This prior is enforced by constraining each spectra to be described by only few atoms of a dictionary using sparse coding technique (Mairal et al., 2010). This dictionary is built from a set of spectra of black bodies at different temperatures. This method has been successfully applied on the Herbig Be star HD98922. On the reconstructed temperature map, the temperature difference between the star and the surrounding environment is clear and the mean temperature of the disk is estimated to be 1670 K, very close to the one estimated from photometry.

9907-139, Session PSTh

Science with MATISSE

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MATISSE, the Multi Aperture Mid-Infrared SpectroScopic Experiment (Lopez et al. 2014), is foreseen as a mid-infrared spectro-interferometer combining the beams of up to four UTs/ATs of the Very Large Telescope Interferometer (VLTI). MATISSE will measure closure phase relations and thus offer an efficient capability for image reconstruction. In addition to this, MATISSE will open two new observing windows at the VLTI: the L and M band in addition to the N band. Furthermore, the instrument will offer the possibility to perform simultaneous observations in separate bands. MATISSE will also provide several spectroscopic modes with spectral resolutions up to 5000. These modes will provide unique insight in the physical properties and kinematics of line emitting gas regions, for example in the environment of YSOs and hot stars.

MATISSE will extend the astrophysical potential of the VLTI by overcoming the ambiguities often existing in the interpretation of simple visibility measurements. The existence of the four large apertures of the VLTI will permit to push the sensitivity limits up to values required by selected astrophysical programs such as the study of Active Galactic Nuclei and protoplanetary disks around low-mass stars. Moreover, the existence of ATs which are relocatable in position will allow the exploration of the Fourier plane with up to 200 meters baseline length. Key science programs using the ATs cover for example the formation and evolution of planetary systems, the birth of massive stars as well as the observation of the high-contrast environment of hot and evolved stars.

In most astrophysical domains which require a multi-wavelength approach, MATISSE will be a perfect complement of high angular resolution facilities. MATISSE covers the mid-infrared spectral domain, between the near-infrared domain, for which various high-angular resolution instruments are available (e.g., SPHERE/VLTI, PIONIER/VLTI) and submillimeter/millimeter wavelengths at which ALMA, the Atacama Large Millimeter Array, operates. With the extended wavelength coverage from the L to the N band, MATISSE will not only allow one to trace different spatial regions of the targeted objects, but also different physical processes and thus provide insights into previously unexplored areas, such as the investigation of the distribution of volatiles in addition to that of the dust.

Based on the general characteristics of MATISSE, we will present a general overview of the scientific potential of this instrument as well as selected case studies from various areas, such as star and planet formation, active galactic nuclei, evolved stars, extrasolar planets, and solar system minor bodies. We will discuss strategies for the planning and analysis of future MATISSE observations. Moreover, the impact of MATISSE observations in combination with complementary high-angular resolution observations at near-infrared and submillimeter/millimeter wavelengths will be highlighted.

9907-140, Session PSTh

Observing the PTPS sample of evolved exoplanet host candidates using the NPOI

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We plan to measure the angular diameters of a sample of Penn State-Torun Planet Search (PTPS) giant exoplanet host star candidates using the Navy Precision Optical Interferometer. The radii of evolved giant stars obtained using spectroscopy are usually ill-defined because of the method's indirect nature and evolutionary model dependency. The star's radius is a critical parameter used to calculate luminosity and mass, which are often not well known for giant stars. Therefore, this problem also affects the orbital period, mass, and surface temperature of the planet. Our interferometric observations will significantly decrease the errors in these parameters.

9907-141, Session PSTh

Unveiling new stellar companions from the PIONIER exozodi survey: follow up

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In 2012, we have conducted a survey of nearby main sequence stars with VLTI/PIONIER to search for the presence of circumstellar dust. This survey, carried out during 12 nights, comprised about 100 stars. For each star, we obtained typically three OBs and we searched for circumstellar emission based on the measurement of squared visibilities at short baselines. A drop in the measured visibilities with respect to the expected photospheric visibility indicated the presence of resolved emission around the target star. It was however generally not possible to conclude on the morphology of the detected emission based solely on the squared visibilities. This is why we focused on closure phases to search systematically for faint companions around the whole sample. In our method, we used the closure phases and the square visibilities in a combined way to provide a better systematic rejection of false positive detection.

We reached the conclusion that 4 out of our 13 candidate infrared excesses were actually binaries, which allowed us to identify a clean sample of 9 real excesses.This information also helped us to refine statistics about binaries in our neighborhood. Indeed, since the four binaries were A type stars, we came to the conclusion that 47% of A type stars are binaries in our neighborhood.In 2014, we carried out follow up observations of those targets to confirm that the four stars are bound binaries.Three of them were confirmed, and we found another previously unknown binary. Preliminary constraints on the orbits can be derived on the three companions imaged in 2012 and 2014. Only HD202730 remains ambiguous, as the companion detected in 2012 was not recovered in 2014. Kinematic constraints suggest that HD202730B could still be a bound companion to HD202730, but that it should have a semi-major axis of at least 0.93 AU. We cannot conclude about the eccentricity of this binary based on the existing data.

9907-142, Session PSTh

The optical interferometry data base: how to make the best use of reduced data

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The Optical interferometry DataBase (OiDB) aims at facilitating the access to science-ready data provided by various existing or decommissioned interferometers.

The first version of OiDB has been released in June 2015. Today it contains more than 5000 OIFITS datafiles including the full collection of PIONIER data since 2011. All these reduced data are made publicly available and easily downloadable by OiDB.

The OiDB conditions of use were designed so that the data user collaborates with the team that obtained the data. Fast metadata forms allow an efficient upload of data, making OiDB an ideal platform to diffuse interferometric data from any observatory. Moreover, OiDB also provides regularly updated observation logs from some CHARA instruments.

After presenting the characteristics of OiDB, we analyse how the community made use of it during this first year of operation. We will also show how new features make this tool more interactive, more connected to other virtual observatory tools and to article citations.

9907-143, Session PSTh

Searching for exozodiacal light around main sequence stars with JouFLU/CHARA

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JouFLU is the upgraded Fiber-Linked Unit for Optical Recombination, located at the CHARA array. The use of single-mode optical fibers of JouFLU allows removing atmospherically induced wave-front distortions (except for atmospheric piston), which results in more precise (~1%) visibility measurements. FLUOR was used by Absil et al. (2013) to search for near-infrared exozodiacal light in the vicinity (0.1 AU - 10 AU) of 42 main-sequence stars, and found 11 stars that display a K-band excess that is consistent with uniform extended emission. The circumstellar excess is likely attributed to hot circumstellar-dust, whose origin is still poorly understood.

Since 2013, JouFLU has been extending the survey and performing follow-up observations of previously observed targets. These studies aim to search for correlations between near-infrared excesses and basic stellar parameters, as well as the detection of a mid/far-infrared excess. So far we have added 30+ main-sequence stars to the survey, and 14 follow-up observations. We have also developed a new data analysis pipeline which has been tested by performing angular diameter measurements as well as an independent analysis of the data obtained by Absil et. al (2013), which agrees with published results. Our preliminary analysis of the recent data reveals 4 new detections of extended circumstellar emission and 2 excesses that are likely due to binarity. Our preliminary analysis of follow-up observations indicates that the circumstellar emission may be variable for at least 2 targets.

9907-144, Session PSTh

Co-phasing the planet formation imager

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The Planet Formation Imager (PFI) is a projected very large post-VLTI infrared interferometer intended to obtain images of the planet formation process, down to the Hill sphere of a Jupiter mass giant exoplanet in some of the closest star forming regions. This resolution requires baselines up to 10 Km and the need for high contrast imaging implies the use of at least 20 apertures. The science windows of PFI are in the thermal infrared but the array must be cophased in the near infrared K or, more likely, H bands. The limiting sensitivity of PFI will be set by the capacity to cophase the array, i.e. to measure and actively correct the optical path variations introduced by the atmosphere down to a fraction of wavelength. This sensitivity depends on the size of the individual apertures and the performance of the fringe tracker. Observing typical solar mass young stellar objects in nearby (100 to 250 pc) star forming regions implies cophasing on objects with correlated magnitudes of H>9 (e.g. an inner-disk free H~9, or H~8 with a ~50% disk contribution) Observing the full range of targets (including e.g. HL Tau) needs a correlated magnitude limit of H>10 with critical baselines of typically 1 Km. In the currently used fringe trackers, the sensitivity decreases with the number nT of apertures and reaching H>10 with nT>20 would require individual diameters larger than 10 m. This would quite certainly make the PFI project far too expensive. In this paper we evaluate alternative FT architectures in order to achieve the desired sensitivity with much smaller apertures. In the Chain FT (CFT), each telescope is cophased with only two other apertures and each flux is divided only by two, whatever nT. In the Hierarchical Fringe Tracker (HFT), we cophase pairs of apertures, then pairs of pairs and then pairs of groups and the limiting sensitivity is this of a two-telescope interferometer independently of nT. If PFI can be cophased with an HFT, it could use 2-3 m individual apertures. We also investigate arrays that are only coherenced within a few wavelengths and the possibilities of off-axis cophasing and coherencing in special sites to try either to show that PFI can be done with telescopes smaller than 2 m or that a PFI with 3 m apertures could also be used for observations of AGNs with magnitudes K>13.

9907-145, Session PSTh

Practical beam transport for PFI

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The Planet Formation Imager (PFI) is a future facility to image the process of planetary formation. The key science driver is the resolution of sub-Hill sphere structures around giant proto-planets orbiting solar-type stars in nearby star forming regions. Operating at wavelengths around 10 micron, PFI will require at least 20 telescopes separated by maximum baselines of 5 to 10 km. Heterodyne and homodyne (direct detection) interferometer designs are being studied for PFI. Both options will require near-IR homodyne fringe tracking. Technologies that could be used to transport starlight from the telescopes to a beam-combining laboratory include free-space propagation in air (with adaptive optics to mitigate atmospheric turbulence effects) or in vacuum, and optical fibres. Free-space propagation (usually in vacuum) is the solution typically adopted at more modest scale infrared interferometers, and this paper addresses the design and cost issues associated with following such an approach for PFI. We present straw-man beam-relay designs for pseudo-circular and Y-shaped telescope arrays, and discuss their advantages and disadvantages. The results of Fresnel diffraction calculations predicting the worst-case coherence losses are presented, and used to determine optimum beam diameters for the two types of array layout.

9907-146, Session PSTh

A high-precision thermal near-infrared instrument for the VLTI

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The development of high dynamic range capabilities has long been recognized as one of the top priorities for the VLTI. In the era of extremely large telescopes, the VLTI will remain a major observational tool as the only southern instrument able to probe the smallest spatial scales of nearby planetary systems. As of today, the VLTI can achieve a dynamic range of a few 100:1 in the near-infrared and second-generation instruments are not designed to improve that limit. Other interferometers in the northern hemisphere have however demonstrated that a dynamic range of 1000:1, or even higher, is within reach. In this paper, we first review the state of the art regarding high-precision infrared interferometry and then present a preliminary instrumental concept of a possible high-precision four-telescope VLTI instrument. The instrumental concept combines several features that made the success of other high-precision interferometric instruments such as integrated optics, closure phase, nulling, and statistical data reduction. In particular, recent advent in lithium niobate technology now opens the possibility to manufacture integrated optics components that operate in the thermal near-infrared (3-5 microns), a sweet spot to image and characterize young extra-solar planetary systems. We describe the expected performance of a high-precision thermal near-infrared instrument and briefly address its science cases, which mainly consist of extrasolar planetary science (exoplanets, exozodiacal disks, and planet-forming regions) but also include stellar physics and active galactic nuclei.

9907-147, Session PSTh

Cost models for the Planet Formation Imager

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We examine cost drivers for the Planet Formation Imager (PFI) project. This includes the following major infrastructure elements: telescopes, adaptive optics, beam transport, beam delay, fringe tracking instrumentation, scientific beam recombination, on-sky operations control, and data infrastructure (including data reduction pipelines). In part, the economics of these items - including economies of scale - will drive architecture decisions for PFI. Reconciling the intersection of optimimum cost with highest scientific return will be a key design goal of the facility.

9907-148, Session PSTh

The Wide-field Imaging Interferometry Testbed (WIIT): analysis and synthesis of measured and simulated data

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The Wide-field Imaging Interferometry Testbed (WIIT) is a double Fourier interferometer (DFM) operating at optical wavelengths, and provides data that are highly representative of those from a space-based far-infrared interferometer like SPIRIT. This testbed has been used to measure both a spatial and spectrally simple test scene and a more complex and astronomically representative test scene. Here we present the simulation of recent WIIT measurements using FIInS (the Far-infrared Interferometer Instrument Simulator), which main goal is to simulate both the input and the output of a DFM system, and compare the input map with the synthesized one after data processing. The results from FIInS are compared with the results obtained from recent measurements with WIIT.

9907-149, Session PSTh

Stray light evaluation for the astrometric gravitation probe mission

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The main goal of the Astrometric Gravitation Probe (AGP) mission is the verification of General Relativity (GR) and competing gravitation theories by precise astrometric determination of light deflection, and of orbital parameters (e.g., the effect of pericentre excess shift) of selected Solar System objects. The bending of the light path due to the gravitational pull of massive bodies is in fact one of the best known effects introduced by GR. One of the earliest confirmations of Einstein's GR theory was obtained by Dyson, Eddington and Davidson during the May 29th, 1919 solar eclipse.

Their experiment, as well as subsequent attempts during the XX century, was strongly constrained to 10% precision by the eclipse short duration and location (imposing usage of small portable instruments), and by atmospheric turbulence.

More recent measurements, mainly from space, currently achieve the \$10^{-5}\$ level on the \$gamma\$ and \$beta\$ parameters of the Parametrized Post-Newtonian (PPN) formulation of gravitation theories.

The AGP mission is conceived to achieve a precision level corresponding to \$10^{-8}\$ on \$gamma\$ and \$10^{-6}\$ on \$beta\$, much better than any other astronomical experiment planned for the forthcoming years.

The telescope optical design is an evolution of the GAME (Gai et al., Proc. SPIE 9150, 2014) and ISAS (Gai et al., Proc. SPIE 8446, 2012) concepts, and it is based on a classical Korsch Three Mirror Anastigmatic telescope configuration.

The key element is the coherent combination of a set of 92 circular entrance apertures, each feeding an elementary inverted occulter similar to the one developed for Solar Orbiter/METIS and described in Landini et al., Proc. SPIE 8862, 2013.

This provides coronagraphic functions over a relevant field of view, in which all stars are observed for astrometric purposes with the full resolution of a 1 m diameter telescope.

The telescope primary mirror acts as a beam combiner, feeding the 92 pupils, through the internal optics, toward a single focal plane.

The primary mirror is characterized by 92 output apertures, sized according to the entrance pupil and telescope geometry, in order to reject the solar disk light by dumping it beyond the instrument.

The astronomical objects are much fainter than the solar disk, which is angularly close to the inner field of view of the telescope.

The stray light as generated by the diffraction of the solar disk at the edges of the 92 apertures defines the limiting magnitude of observable stars.

In particular, the stray light due to the diffraction from the pupil apertures is scattered by the telescope optics and follows the same optical path of the astronomical objects; it is a contribution that cannot be eliminated and must therefore be carefully evaluated.

This paper describes the preliminary evaluation of this stray light contribution.

The whole solar disk is considered as a source and a limb darkening model is included as well.

9907-150, Session PSTh

Opto-mechanical design of AGP (Astrometric Gravitation Probe)

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This paper describes the current opto-mechanical design of AGP (Astrometric Gravitation Probe).

The Astrometric Gravitation Probe (AGP) mission is designed for astrometric verification of General Relativity (GR) and competing gravitation theories by means of precise determination of light deflection on field stars, and of orbital parameters (e.g., pericentre excess shift) of selected Solar System objects.

The bending of the light path due to the gravitational pull of massive bodies provided one of the earliest confirmations of Einstein's GR theory, by the measurements of Dyson, Eddington and Davidson during the May 29th, 1919, solar eclipse.

Recent measurements, mainly from space, currently achieve the 10^{-5} level on the $gamma$ and $beta$ parameters of the Parametrized Post-Newtonian (PPN) formulation of gravitation theories.

The AGP mission is conceived to achieve a precision level corresponding to 10^{-8} on $gamma$ and 10^{-6} on $beta$, much better than any other astronomical experiment planned for the forthcoming years.

We briefly review the mission concept to derive the instrument and operation requirements, then proceeding to the design definition based on the guideline of mitigation of systematic errors.

The most innovative aspect of the instrument is the combination of Fizeau Interferometry and coronagraphy for high precision astrometry close to the Sun. The coronagraphic concept and performance is discussed in the paper by Landini et al. [this conference].

Furthermore, the optical concept includes a planar rear-view mirror for simultaneous imaging on the CCD mosaic detector of fields of view (FOV) also from the direction opposite to the Sun, affected by negligible deflection, for the sake of real time calibration.

Other relevant issues are nearly constant Sun/Earth pointing, instrument stability at the milli-arcsec (mas) level and imaging quality. Reversal of the lines of sight over each orbit is used to ensure that instrumental characteristics are introduced mostly as common mode.

The precision of astrometric measurements on individual stars will be of order of 1 mas, over two fields separated by few degrees around the Sun and observed simultaneously. The proposed design retains the angular resolution of a 1 m telescope, in spite of the trade-offs imposed by adoption of a coronagraphic system and multiple lines of sight.

We describe the optical design characteristics, with particular reference to manufacturing and tolerancing aspects, evidencing the preservation of very good imaging performance over the range of expected operating conditions.

We also present the proposed mechanical solution, discussing the implications of thermo-elastic disturbances and evidencing their efficient cancellation in the measurement combination.

Finally, we report on the current error budget and discuss the technological development plan.

9907-49, Session 23

Hierarchical fringe tracker to co-phase and coherence very large optical interferometers

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The limiting sensitivity and often the accuracy and dynamical range of optical interferometers is set by the architecture of the Fringe Tracker (FT) used to cophase or to coherence the array. With conventional fringe tracking concepts, such as the pairwise approach of the 2nd generation VLTI instrument GRAVITY, the cophasing sensitivity decreases with the number of apertures, which is a growing problem from the current 4 telescopes instruments to the planned 6 apertures combination of CHARA. This problem will be dramatic for a large interferometer such as the Planet Formation Imager (PFI) with more than 20 apertures. In addition, the necessity to measure in real time the group delay of the fringe packet implies the dispersion of the light on several spectral channels, with a cost in limiting sensitivity in the detector noise dominated near-infrared domain that must be used for fringe tracking. These conceptual constraints set a sensitivity limit for the GRAVITY/PIONIER pairwise approach near K~10.5 with the UTs and K~7.5 with the ATs. In comparison, the full scientific potential of the VLTI requires cophasing the UTs up to K>14 for the AGN program and the ATs up to K>9 for the Young Stellar Objects and K>10 for the AGN program. PFI has similar requirements about sensitivity and would need individual apertures larger than 10 m with a pairwise approach.

Here we describe our concept study of an alternative Hierarchical Fringe Tracker (HFT) architecture based on a broad band achromatic 2 beams spatial filter (SF2B) that transmits most of the incoming flux if the two inputs beams are cophased, as produced by a single aperture cophased telescope. When the inputs beams are not cophased, about 50% of the flux is deflected toward a pair of single pixel detectors that measure the piston necessary to cophase the pair. A combination of SF2B allows to cophase pairs of apertures, then pairs of pairs, then pairs of groups with a sensitivity set only by the performance of the broad-band, two telescopes, single channel fringe tracker. The coherencing of the array is obtained by an optimized fluted spectrum dispersed fringe device, derived from the 2D Fourier Transform group delay processing that we have used to boost the limiting sensitivity of the VLTI instrument AMBER. This paper describes the numerical simulations and the experiments to validate the SF2B and discusses the optimization of its performances. It evaluates the global HFT performance and discusses its control architecture. We show that an HFT would allow operating the VLTI beyond K~15 with the UTs and K~11 with the ATs. It would also allow building a "more than 20 apertures" PFI with individual telescopes in the 2-3 m diameter range. We discuss also the use and optimization of the HFT for bootstrapping an interferometer with very low fringe contrast on its longer baselines.

9907-50, Session 23

Simultaneous water vapor and dry air optical path length measurements and compensation with the Large Binocular Telescope Interferometer

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The Large Binocular Telescope Interferometer uses a near-infrared camera to measure the optical path length variations between the two AO-corrected apertures and provide high-angular resolution observations for all science channels (1.5-13 microns). There is however a wavelength dependent component to the atmospheric turbulence, which can introduce optical path length errors when observing at a wavelength different from that of the fringe sensing camera. While generally a small contributor to the atmospheric refractive index at infrared wavelengths, the water vapor component of the atmospheric seeing must nevertheless be taken into account for high-precision infrared interferometric observations as described previously in the context of the Keck Interferometer Nuller. In this paper, we present the new sensing approach that has been developed at the LBT to measure the optical path length fluctuations due to dry air and water vapor separately. We describe both the new optical setup and the computation of the N-band feedforward quantities from the K-band measurements. Simultaneous H, K and N-band sky data are presented to illustrate both the good correspondence with the underlying atmospheric models and the improvement in the co-phasing stability in the mid-infrared. Finally, we review the current performance and limitations of the system and discuss briefly their implications for the LBTI exozodiacal dust survey (i.e., getting stellar nulls to accuracy levels of 10-4 in the mid-infrared).

9907-51, Session 24

Long baseline interferometry in the visible: first results of the FRIEND project

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In the coming year, the CHARA 1-meter telescopes will be equipped with Adaptive Optics (AO) systems. This improvement opens the possibility to apply, in the visible domain, the principle of spatial filtering with single mode fibers well demonstrated in the near-infrared. It will clearly open new astrophysical fields by taking benefit of an improved sensitivity and state-of-the-art precision and accuracy on interferometric observables. A demonstrator called FRIEND (Fibered and spectrally Resolved Interferometric Experiment - New Design) has been developed. FRIEND combines the beams coming from 3 telescopes after injection in single mode optical fibers and provides some spectral capabilities for characterization purposes as well as photometric channels. It operates in the R spectral band (from 600nm to 750nm) and uses the fast and sensitive analogic detector OCAM2. On sky tests at the focus of the CHARA interferometer have been performed during the last year. Complementary lab tests have permitted to characterize the polarization behavior of the prototype, including detector characteristics. In this paper, we present the results of these tests and our conclusion for the development of the science instrument.

9907-52, Session 24

Towards a new generation 6T visible instrument for the CHARA array and VLTI perspectives

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The recent progresses made on the FRIEND prototype, the planning of the AO development on CHARA and the increased performance required for the enhancement of important scientific programs in the visible have led to the start of a system analysis of a new generation 6T visible beam combiner for CHARA with potential perspectives for the VLTI Array. Its specification will be based on potential large programs of general interest like massive stellar parameters determination.

In this paper we present the current status of the various activities from the science specifications, the detector and beam combiner principles, up to the detailed analysis of injection optimization, polarization control and fringe tracking requirements. A conceptual design will be presented with the main important specifications and a study of the potential performance will be presented.

9907-53, Session 24

Building a hypertelescope: prototype testing and perspective toward kilometric versions

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The spherical Arecibo geometry, and the nearly spherical active paraboloïd adopted for the FAST radiotelescope, are of interest for a large dilute optical aperture with hundreds of small mirrors. It requires no delay lines, just actuators for adaptive co-phasing toward direct high-resolution images. These are obtainable at the combined focus in the Fizeau mode, with field extent limited by the field aberrations of the large meta-mirror, or in the "hypertelescope" mode, using a small pupil-densifier element added downstream for a more efficient light concentration in images of compact sources. The latter mode divides the Fizeau field into an array of narrow sub-fields with gaps between them, which can match multiple sources such as globular clusters, galaxies, etc... Also, several focal gondolas, equipped with different visible or infra-red detectors, coronagraphs, etc... and independantly tracking different sources, can be operated at the same time. The basic architecture is suitable both for terrestrial versions, at suitable concave mountain sites, and for space versions employing a dilute flotilla of mirrors, eventually as large as 100,000km.

Among the initial science targets are exoplanets in near-transit position, for which direct images showing the crescent of grazing starlight refracted by their atmosphere can be recorded in a coronagraphic mode, together with spectra containing planet's atmospheric information.

We have verified, at the scale of a 200m meta-aperture, the feasibility and operability of terrestrial hypertelescopes. A smoothly curved high valley of the southern Alps has been equipped with a few initial tripods, anchored and adjusted to carry small (15cm) mirrors on the spherical locus. A focal gondola is suspended, 101m above them, from a traversing cable, and driven, for tracking the star image, by six oblique wires tensioned by computerized winches. The specified tracking accuracy of the gondola, one millimeter, proved achievable with manual feedback in low-wind conditions, frequent during anticyclonic weather. In the absence yet of a camera aboard the focal gondola, a small mirror has relayed a coudé focus at ground level. An image of Vega could be observed there, but from a single sub-aperture and thus not yet containing fringes.

Plans are made for the adaptive cophasing and tip-tilt correction, using a modified wave sensor. For early science, non-cophased exposures can be initially recorded in a Speckle Imaging mode to generate reconstructed images (Surya et al., 2011). Also to be tested is a "Hypertelescope Laser Guide Star", already explored in the laboratory by Labeyrie (2013) and Nunez et al. (2014), which differs from the versions serving for conventional telescopes and ELTs. Although requiring appreciable laser power, it may extend high-resolution Earth-based observing to very faint sources, pending space hypertelescopes.

Tests of a "flying gondola", using a small balloon-assisted electric drone, are also foreseen for further simplifying the hypertelescope's architecture, which is already much simplified with respect to conventional interferometers featuring complex optical trains, and costly optical delay lines which have drastically limited the number of their subapertures. If validated, the "flying gondola" scheme may provide kilometric meta-apertures.

9907-54, Session 25

Planet Formation Imager: science vision and key requirements

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Despite recent advancements, many fundamental questions still surround the processes that are involved in planetary birth: Where in the protoplanetary disk do the planets form and how do they grow? What factors determine the final architecture of planetary systems? How are water and other volatiles delivered to the protoplanets and how does this affect the potential habitability of these worlds? The aim of the Planet Formation Imager (PFI) project is to answer these questions by witnessing the planetary formation process on the natural spatial scales where the material is assembled, which is the Hill sphere of the forming planets. PFI will detect giant protoplanets on all stellocentric radii, image their interaction with the ambient disk material, and trace their dynamical evolution during the first 100 million years, thereby reveal the processes that determine the architecture of planetary systems.

Starting from the initial thoughts outlined in a 2014 SPIE paper, the PFI science working group has worked on refining and quantifying the science drivers for PFI. Our 70+ contributors investigated the observational characteristics of young planets, the migration mechanisms that alter the system architecture, and the imprints that the planets leave in the disk from the pre-main-sequence to the debris disk phase. We also studied intriguing secondary science cases in exoplanet science, stellar astrophysics, and extragalactic astronomy. Our aim is to publish a comprehensive science whitebook in the second half of 2016.

This talk will present our main findings and discuss the key science requirements that will guide the technology choices, the site selection, as well as potential science/technology tradeoffs. The associated proceedings paper will serve as an executive summary of the comprehensive (200+ pages) whitebook.

9907-55, Session 25

Status of the Planet Formation Imager (PFI) concept *(Invited Paper)*

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More than 2 decades ago, the first accepted detection of an extrasolar planet greatly broadened and accelerated our understanding of planet formation. Today, after more than a thousand of radial velocity detections, some direct imaging detections and a treasure trove of data from Kepler, many of the key elements of the planet formation process are now understood to a limited extent. At the heart of our current uncertainties is the period of giant planet assembly where processes of grain growth, protoplanet assembly, magnetic fields, disk/planet dynamical interactions and complex radiative transfer all come together to both form the last giant planets in a solar system and determine the conditions for habitable terrestrial planet formation. The Planet Formation Imager (PFI) project aims to image this period of planet assembly directly, resolving structures as small as a giant planet's Hill sphere. This capability will also enable many auxilliary science cases. We will present the overall vision for the PFI concept, focusing on the key facility requirements that are needed to achieve the science goals. For example, we will show that only the direct detection concept can probe gas tracers in the 3-5 micron window, which may be critical for directly measuring exoplanet masses. For the direct detection design, we will outline key elements with known costs and key cost uncertainties for a baseline design. Important details (for example on the technology roadmap, detailed design and subsystems) will be given other presentations in this conference.

9907-56, Session 26

Imaging planet formation: heterodyning with mid-IR frequency combs

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We discuss our efforts to build a broadband heterodyne receiver for 10-micron applications using a laser frequency comb local oscillator (LFC-LO). LFC generation (and applications) has thus far been focused in the visible and near-IR. However, mid-IR (MIR) frequency combs are of growing interest in astrophysics because they enable dispersed, wide-band, multi-telescope heterodyne interferometry over long baselines, providing imaging for complex scenes and also phase information as compared to traditional direct detection interferometers; A heterodyne receiver based on a comb local oscillator (LO) can enable astronomical observations with spectral bandwidths similar to or exceeding direct detection. This enables observations of planet-formation in the nearest star-forming regions (~150 pc away) on sub-AU scales with conceptual instruments such as the Planet Formation Imager (PFI). The physical scales of interest are the planetary Hill spheres, targeting protoplanetary accretion and fine structure in protoplanetary disks, and catching planets in the act of formation.

For the Earth and planetary sciences, frequency comb spectroscopy is revolutionizing spectroscopic sensing through the simultaneous combination of broad spectral coverage, fast acquisition, and high spectral resolution. Extension of frequency comb technology into the MIR will greatly enhance sensitivity for molecular detection, leading to substantial scientific capabilities and/or cost savings for future missions that monitor greenhouse gases and atmospheric pollution on Earth, as well as those searching for life and biomarkers on solar system bodies.

9907-57, Session 26

Beam combination schemes and technologies for the Planet Formation Imager

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The Planet Formation Imager (PFI) initiative [1] is aiming at developing the next generation large scale facility for imaging astronomical optical interferometry operating in the mid-infrared.

A conceptual technical study is currently underway to identify suitable key technologies for the realization of the facility.

Here we report on the progress of the Technical Working Group on the beam-combination instruments.

Our working baseline scenario considers an array of 20 telescopes and two alternative options for the science beam combination, namely a dispersed heterodyne or a dispersed homodyne scheme. In both cases, fringe tracking at near-infrared wavelengths will be necessary to access faint targets, thus requiring an additional beam-combiner instrument.

Regarding the science beam-combiner(s), we will discuss the various available options for the homodyne scheme ranging from direct imaging [2], to non-redundant fiber arrays [3], to integrated optics (IO) solutions [4,5]. We will consider instrumental aspects such as the throughput, per-baseline sensitivity, numerical stability of the visibility retrieval method, with an eye to the overall SNR of the reconstructed image.

In this context, a strategy to boost per-baseline sensitivity is to combine entangled sub-sets of at least 3 telescopes to obtain visibilities and closure phases over a selected sub-network of baselines. This task could be achieved easily with integrated optics circuits, as recently demonstrated at the Observatory of Paris with an IO 18-telescope, 32-baselines beam combiner operating in H-band.

While a compromise between sensitivity and image reconstruction fidelity should be found, we mention that further technological development is still required to achieve the reliability and throughput of near-infrared IO at longer wavelengths, as required by PFI. In this respect, a promising technology platform for mid-infrared IO is represented by ultrafast laser inscription [6], which can be used to manufacture waveguides with losses as low as 0.2 dB/cm in the L-band.

Concerning the fringe tracker beam combination scheme, near-infrared fringe measurement on a selection of short/intermediate baselines is required. Some level of redundancy in the combination scheme will be necessary to limit the impact of failure of fringe tracking on individual baselines. As for the fringe tracker instrument, we believe that near-infrared IO will play a central role in delivering a stable and compact device with high throughput. As mentioned before, planar IO in near-infrared is already technologically mature to deliver such baselines-selective beam combiners. Additionally, ultrafast laser inscription could be used to avoid cross-overs in the beam combination scheme [6] and thus limit the cross-talk between the combined channels.

[1] J.D. Monnier, et al. Proc. SPIE 9146, 914610 (2014).

[2] D. Mourard, et al. MNRAS 445, 2082 (2013).

[3] E. Huby, et al. A&A 541, A55 (2012).

[4] J.B. Le Bouquin, et al. A&A 535, A67 (2011).

[5] A. Saviauk, et al. Appl. Opt. 52, 4556 (2013).

[6] A. Rodenas, et al. Opt. Lett. 37, 392 (2012).

9907-58, Session 26

Architecture design study and technology road map for the Planet Formation Imager (PFI)

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The Planet Formation Imager (PFI) Project has formed a Technical Working Group (TWG) to explore possible facility architectures to meet the primary PFI science goal of imaging planet formation in situ in nearby star-forming regions. The goals of being sensitive to dust emission on solar system scales and resolving the Hill-sphere around forming giant planets can best be accomplished through sub-milliarcsecond imaging in the thermal infrared. Exploiting the 8-13 micron atmospheric window, a ground-based long-baseline interferometer with approximately 20 apertures including 10km baselines will have the necessary resolution to image structure down 0.1 milliarcseconds (0.014 AU) for T Tauri disks in Taurus. Even with large telescopes, this array will not have the sensitivity to directly track fringes in the mid-infrared for our prime targets and a fringe tracking system will be necessary in the near-infrared. Here, we describe feasible designs for both a “direct detection” and a heterodyne facility, emphasizing their common elements as well as the distinct dis/advantages of each variant. Guided by imaging simulations with realistic signal-to-noise ratios as well as a simple cost model, we will discuss the architecture trade offs in terms of number of telescopes, telescope diameter and efficiency metrics. The required sensitivity metrics for PFI include adaptive optics guide star sensitivity, fringe tracking sensitivity and thermal infrared sensitivity. For the direct detection design, the high thermal infrared sensitivity required means that a high degree of care has to be taken in appropriate cold stops and diffractive effects. We will advocate for a specific technology road map in areas including telescopes, adaptive optics, beam train, fringe sensor and imaging software that will allow PFI to reach its scientific goals with a feasible facility plan. This work will pull together results from multiple sub-groups within the PFI-TWG, some of which will be explored in more detail in other presentations at this meeting (e.g., mid-IR laser combs, beam combiners).

9907-59, Session 27

Interferometry community discussion session *(Invited Paper)*

Stefan Kraus, Univ. of Exeter (United Kingdom)

The international interferometry community is bursting with activity, as it works to deliver a new suite of instruments and major facility infrastructure upgrades (CHARA, NPOI, and VLTI) and to bring a new facility on the sky (MROI). A close coordination & collaboration between facility

representatives, instrument builders, and potential users will be essential in order to implement these advancements successfully and to maximize their scientific return. At the same time, we need to plan the next steps and develop a coherent roadmap for the future development of our field.

SPIE offers an unique forum to discuss these topics, as it brings interferometrists from all facilities and all continents together. In this discussion session, the panelists and attendants will discuss a broad range of topics that are of interest for all communities & facilities or that could benefit from coordination.

Sunday - Thursday 26–30 June 2016

Part of Proceedings of SPIE Vol. 9908 Ground-based and Airborne Instrumentation for Astronomy VI

9908-1, Session 1

The Paranal instrumentation program *(Invited Paper)*

Luca Pasquini, European Southern Observatory (Germany)

The Paranal Instrumentation Programme is responsible for designing and procuring, in collaboration with consortia in the ESO community, all the instruments for the Paranal and La Silla observatories, their upgrades and the upgrade of the infrastructures to host them. I will report about the latest progresses and the future plans to keep the Paranal and La Silla observatories competitive in the E-ELT era.

9908-2, Session 1

Overview of the instrumentation programme of the 10.4m GTC Telescope *(Invited Paper)*

Antonio L. Cabrera-Lavers, Romano L. M. Corradi, GRANTECAN S.A. (Spain)

We will present the instrumentation plan until 2019 of the 10.4m Gran Telescopio Canarias (GTC), located in the island of La Palma.

It includes a suite of instruments covering different wavelength domains (from 350 to 2000 nm), with imaging, multiplexed (MOS, IFUs, and Fabry-Perot) spectroscopy at a resolution R<=30000 and polarimetric capabilities, and adaptive optics correction.

Up to six instruments will be available at the same time, taking advantage of the five, full-equipped and interchangeable focal configurations of GTC, which include one Cassegrain, two Nasmyth, and two Folded-Cassegrain foci.

9908-3, Session 1

Instrumentation at Gemini Observatory *(Invited Paper)*

Scot J. Kleinman, Stephen J. Goodsell, Chadwick A. Trujillo, Gemini Observatory (United States)

I will provide an update of Gemini's new instrument and adaptive optics capabilities. The new Gemini high-resolution optical spectrograph is now in its build phase and will be available to Gemini users in 2018. We have also started our next new instrument, designed to provide valuable support and follow-up for coming new facilities and capabilities in astronomy. Meanwhile, our current instrument upgrade program continues with plans to expand it this year. We continue to improve and stabilize our multi-conjugate adaptive optics system at Gemini South and are making additional upgrades to our Gemini North AO system, Altair.

9908-4, Session 1

New developments in instrumentation at the W. M. Keck Observatory *(Invited Paper)*

Sean M. Adkins, W. M. Keck Observatory (United States); Michael P. Fitzgerald, James E. Larkin, Univ. of California, Los Angeles (United States); Hilton A. Lewis, W. M. Keck Observatory (United States); D. Christopher Martin, Dimitri Mawet, California Institute of Technology (United States); Jason X. Prochaska, Univ. of California, Santa Cruz (United States); Peter L. Wizinowich, W. M. Keck Observatory (United States)

The W. M. Keck Observatory is committed to maintaining the scientific leadership of our observing community by matching our observers' skills and passions in their fields of astronomical science with a continuing dedication by the Observatory and its collaborators to the development of state of the art instrumentation and systems. Our science driven strategic plan guides these developments and informs our plans for the future. In this paper we describe the performance of recently completed new instruments, instrument upgrades, and infrastructure upgrade projects. We also describe the expected performance of projects currently in the development or construction phases. Projects recently completed include the blue channel of the Keck Cosmic Web Imager, a new laser for the Keck II AO system, the upgrade of the spectrograph detector in the OSIRIS instrument, and the upgrade to the telescope control systems on both Keck telescopes. Projects in development include a deployable tertiary mirror for the Keck I telescope, the red channel of the Keck Cosmic Web Imager, an upgrade to the imager of OSIRIS, a major upgrade to the NIRSPEC instrument, and a fiber feed from the Keck II AO system to NIRSPEC.

9908-5, Session 2

An overview of the current and future instrumentation at the Subaru Telescope *(Invited Paper)*

Yosuke Minowa, Naruhisa Takato, Ikuru Iwata, Takashi Hattori, Subaru Telescope, National Astronomical Observatory of Japan (United States)

Subaru telescope has a suite of 7 facility instruments and 2 visitor instruments, which provide imaging and spectroscopic capabilities over the wide range of wavelengths from optical to mid-infared. Recently, a new prime focus optical wide-field imager Hyper Suprime-Cam (HSC), which has 1.5 deg field-of-view (FoV), is commissioned and started its science operation including a large survey program by using 300 nigths over 5 years. A new facility instrument, Prime-Focus Spectrograph (PFS), which is an optical to near-infrared multiplexed spectrograph over 1.3 deg FoV, is currently being developed by an international collaboration led by Kavli IPMU, University of Tokyo. PFS is planning to have an engineering first light for the part of the system in 2018 and to start science operation in 2019. As a next facility instrument in near-infrared, we are investigating the feasibility of wide-field near-infrared imagers and multi-object spectrograph (or IFUs) with ground layer adaptive optics system, which is expected to provide a great seeing improvement (less than 0.2 arcsec in K-band) over a wide field coverage (13x16 square arcmin). Our strategy toward 2020s is to fully utilize the Subaru's wide-field capability using

these three facility instruments. As well as the development for the future wide-field instruments, we are upgrading the existing facility instruments to extend the current capabilities. New infrared detectors H2RG and IFU system will be installed to MOIRCS (multi-objet near-infrared camera and spectrograph), and a fiber-fed multi-object spectrograph module will be installed to HDS (optical high-dispersion spectrograph). In addition to the facility instrument, we are accepting several visitor instruments to perform the science that is not covered by the suite of the facility instruments, especially for exoplanet science, and to test a new technology for future instrumentation. In this talk, we will present an overview of the current status of instrumentation and future development plan at the Subaru telescope.

9908-6, Session 2

The JCMT future instrumentation project *(Invited Paper)*

Jessica T. Dempsey, Paul T. P. Ho, Per Friberg, East Asian Observatory (United States); Dan Bintley, James Clerk Maxwell Telescope (United States); Craig A. Walther, East Asian Observatory (United States); Ming-Tang Chen, Institute of Astronomy and Astrophysics - Academia Sinica (United States)

Under the new operational purview of the East Asian Observatory, the JCMT continues to produce premier wide-field submillimetre science. Now the Observatory looks to embark on an ambitious series of instrumentation upgrades and opportunities to keep the telescope at the bleeding edge of its performance capabilities, whilst harnessing the collaborative expertise of the participating EAO regions and its JCMT partners. New heterodyne instruments include a new receiver at 230GHz, a super array (100+ pixels) at 345GHz (SHARP) and the upgrade possibilities for the continuum camera SCUBA-2. In addition, the opportunities for PI and visiting instruments, including TimePilot and Gismo/Gismo2 will be described.

9908-7, Session 2

LBTO's post-first generation instrumentation

Christian Veillet, Julian C. Christou, Large Binocular Telescope Observatory (United States)

The first generation of facility instruments, i.e. instruments to be proposed to users at first light (or soon after), were developed in parallel with the telescope. There are three pairs of such instruments devoted to (1) wide-field imaging (LBC), (2) visible (MODS), and (3) near infrared (LUCI) imaging and spectroscopy. The commissioning of MODS2 and LUCI2 were completed by the end of the first semester of 2016 and all instruments can now be used in binocular mode. With two adaptive secondaries, LBTO provides exquisite diffraction-limited performances, and a GLAO system, ARGOS, should be commissioned by early 2017.

In parallel, two interferometers were developed: LBTI, which produced its first scientific publications in 2015, and LINC-NIRVANA, which arrived at the observatory in the fall of 2015 and will be installed on the telescope as "Lean-MCAO", a limited field MCAO near-infrared imager (fist light by the end of 2016) without interferometric capabilities.

LBTO is now contemplating the expansion of its instrument suite to better benefit from the excellent performance of its Adaptive Optics. Four projects using the LBT at its 8.4m mirrors diffraction limit are contemplated: a near-infrared imager/coronagraph with IFU capabilities (SHARK-NIR) and its analogue in the visible (V-SHARK), iLocater, an ultra-precise near-infrared diffraction-limited spectrometer, and an upgrade of Lean-MCAO, a wide-field multi-conjugate imager.

However, the uniqueness of the telescope resides in its interferometric imaging capabilities, which would be strengthened by the further development of LBTI and the evolution of Lean-MCAO to an interferometric instrument, thus reinforcing the role of LBTO as the first of the ELTs.

These options and their challenges at a time of limited funding and operational limitations will be presented.

9908-8, Session 2

The European Solar Telescope *(Invited Paper)*

Sarah A. Matthews, Mullard Space Science Lab. (United Kingdom) and Univ. College London (United Kingdom); Manuel Collados Vera, Instituto de Astrofísica de Canarias (Spain)

The European Solar Telescope (EST) is a planned 4-metre class solar telescope that is being designed to optimize studies of the magnetic coupling between the lower layers of the solar atmosphere (the photosphere and chromosphere) in order to investigate the origins and evolution of the solar magnetic field and its role in driving solar activity. In order to achieve this, the thermal, dynamic and magnetic properties of the solar plasma must be probed over many scale heights, requiring the use of multi-wavelength spectroscopy and spectropolarimetry at high spatial, spectral and temporal resolution, and the EST project will specialize in the development of cutting edge instrumentation to address these questions. This presentation will present an overview of the main science drivers for EST, the current status and challenges, as well as complementarity with current and future ground and space-based solar instrumentation.

9908-9, Session 3

SITELLE: CFHT's new imaging FTS, early science results

Laurent Drissen, Univ. Laval (Canada); The Sitelle Team, Univ Laval (Canada)

We present the first science results obtained with SITELLE at the Canada-France-Hawaii telescope, during the commissioning run (August 2015) and the Science Verification phase (January 2016). SITELLE is an imaging Fourier transform spectrometer (iFTS), designed to obtain the spectrum of extended emission-line sources in a 11x11 arcminute field of view, with a spatial sampling of 0.32 arcsecond/pixel, in selected bandpasses of the visible range (350 - 850 nm). Hyperspectral data cubes of various objects (Milky Way nebulae and star clusters , nearby galaxies, distant galaxy clusters, Lyman-alpha galaxies) have been obtained at spectral resolutions R ~ 400 - 4000 in order to demonstrate SITELLE's capabilities and potential for discoveries. SITELLE's on-sky performance is as expected, in terms of sensitivity and line spread function. It allows to study of the very important diagnostic [OII] 3727 diagnostic line in HII regions, to map the velocity field of the ionized gas in interacting galaxies with very high accuracy, and to detect dozens of star-forming galaxies in z = 0.15 - 0.25 clusters. Although iFTS are not optimized for continuum and absorption line work because of their well-known distributed noise disadvantage, we also show that SITELLE can provide high-quality spectra of stars in the Milky Way and stellar populations in galaxies.

9908-10, Session 3

FLITECAM: delivery and performance on SOFIA

Sarah E. Logsdon, Ian S. McLean, Univ. of California, Los Angeles (United States); Eric E. Becklin, Ryan T. Hamilton, William D. Vacca, SOFIA / USRA (United States)

We present a performance report for FLITECAM, a 1-5 micron imager and spectrograph, upon its acceptance and delivery to SOFIA (Stratospheric Observatory for Infrared Astronomy). FLITECAM has two observing configurations: solo configuration and 'FLIPO' configuration, which is the co-mounting of FLITECAM with the optical instrument HIPO (PI Edward Dunham, Lowell Observatory). FLITECAM was commissioned in the FLIPO configuration in 2014 and flew in the solo configuration for the first time in Fall 2015, shortly after its official delivery to SOFIA. Here we quantify FLITECAM's imaging and spectral performance in both configurations and discuss the science capabilities of each configuration, with examples from in-flight commissioning and early science data. As expected, the solo configuration (which comprises fewer warm optics) has better sensitivity at longer wavelengths. We also discuss the causes of excess background detected in the in-flight FLITECAM images at low elevations and propose possible solutions.

9908-11, Session 3

300 nights of science with IGRINS at McDonald Observatory

Gregory Mace, The Univ. of Texas at Austin (United States); Hwihyun Kim, The Univ. of Texas at Austin (United States) and Korea Astronomy and Space Science Institute (Korea, Republic of); Daniel T. Jaffe, The Univ. of Texas at Austin (United States); Chan Park, Jae-Joon Lee, Korea Astronomy and Space Science Institute (Korea, Republic of); Kyle Kaplan, The Univ. of Texas at Austin (United States); In-Soo Yuk, Moo-Young Chun, Korea Astronomy and Space Science Institute (Korea, Republic of); Soojong Pak, Kyung Hee Univ. (Korea, Republic of); Kang-Min Kim, Korea Astronomy and Space Science Institute (Korea, Republic of); Jeong-Eun Lee, Kyung Hee Univ. (Korea, Republic of); Christopher A. Sneden, The Univ. of Texas at Austin (United States); Melike Afsar, Ege Üniv. (Turkey); Michael D. Pavel, MIT Lincoln Lab. (United States); Hanshin Lee, The Univ. of Texas at Austin (United States); Heeyoung Oh, Ueejeong Jeong, Korea Astronomy and Space Science Institute (Korea, Republic of); Sunkyung Park, Kyung Hee Univ. (Korea, Republic of); Benjamin T. Kidder, The Univ. of Texas at Austin (United States); Hye-In Lee, Huynh Anh Nguyen Le, Kyung Hee Univ. (Korea, Republic of); Kevin Gullikson, The Univ. of Texas at Austin (United States); Michael Gully-Santiago, Kavli Institute for Astronomy and Astrophysics (China); Jae Sok Oh, Sungho Lee, Young Sam Yu, Narae Hwang, Byeong-Gon Park, Korea Astronomy and Space Science Institute (Korea, Republic of)

The Immersion Grating Infrared Spectrometer (IGRINS) is a revolutionary instrument that exploits broad spectral coverage at high-resolution in the near-infrared. There are no cryogenic mechanisms in IGRINS and its high-throughput white-pupil design maximizes sensitivity. IGRINS on the 2.7 meter Harlan J. Smith Telescope at McDonald Observatory is nearly as sensitive as CRIRES at the 8 meter Very Large Telescope. However, IGRINS at R=45,000 has more than 30 times the spectral grasp of CRIRES. IGRINS employs a silicon immersion grating as the primary disperser of the white pupil, and volume-phase holographic gratings cross-disperse the H and K bands onto Teledyne Hawaii-2RG arrays. The use of an immersion grating facilitates a compact cryostat while providing simultaneous wavelength coverage from 1.45 - 2.45 microns. Here we summarize the performance of IGRINS from the first 300 nights of science since commissioning in Summer 2014. With IGRINS, observers have targeted Solar System objects like Pluto and Ceres, comets, nearby young stars, star forming regions like Taurus and Ophiuchus, the interstellar medium, photodissociation regions, the Galactic Center, planetary nebulae, galaxy cores and super novae. The rich near-infrared spectra of these objects motivate unique science cases, which then provide information on instrument performance. There are more than seven submitted IGRINS papers and dozens more in preparation. With IGRINS, we realize signal-to-noise ratios greater than 100 for K=10.3 magnitude sources in one hour of exposure time. Although IGRINS is Cassegrain mounted, instrument flexure is sub-pixel thanks to its compact design. Detector characteristics and stability have been tested regularly, allowing us to adjust the instrument operation and improve science quality. Science observations have motivated many new tools for analyzing high-resolution spectra including multiplexed spectral extraction, atmospheric model fitting, rotational velocity, radial velocity, unique line identification, and circumstellar disk modeling. Here we discuss details of instrument performance, give example results, and show the characteristics of IGRINS as a versatile near-infrared spectrograph and forerunner of future immersion grating spectrographs.

9908-12, Session 3

VISIR upgrade overview: all's well that ends well

Florian Kerber, Hans-Ulrich Käufl, European Southern Observatory (Germany); Konrad Tristram, Daniel Asmus, Pedro Baksai, European Southern Observatory (Chile); Nicola Di Lieto, Danuta Dobrzycka, European Southern Observatory (Germany); Philippe R. Duhoux, European Southern Observatory (Chile); Gert Finger, Christian Hummel, Derek J. Ives, Gerd H. Jakob, Leander H. Mehrgan, European Southern Observatory (Germany); Eric J. Pantin, CEA-Ctr. de SACLAY (France); Miguel Riquelme, European Southern Observatory (Chile); Stefan Sandrock, Ralf Siebenmorgen, Jörg Stegmeier, European Southern Observatory (Germany); Alain Smette, European Southern Observatory (Chile); Julian Taylor, Mario van den Ancker, European Southern Observatory (Germany); Guillermo Valdes, European Southern Observatory (Chile); Lars Venema, ASTRON (Netherlands)

We present an overview of the VISIR instrument after its upgrade and return to science operations. VISIR is the mid-infrared imager and spectrograph at ESO's VLT. The project team is comprised of ESO staff and members of the original VISIR consortium: CEA Saclay and ASTRON. The project plan was based on input from the ESO user community with the goal of enhancing the scientific performance and efficiency of VISIR by a combination of measures: installation of improved hardware, optimization of instrument operations and software support. The cornerstone of the upgrade is the 1k by 1k Si:As AQUARIUS detector array (Raytheon) which has been carefully characterized in ESO's IR detector test facility (modified TIMMI 2 instrument). A new prism spectroscopic mode covers the N-band in a single observation. New scientific capabilities for high resolution and high-contrast imaging will be offered by sub-aperture mask (SAM) and

phase-mask (AGPM) coronagraphic modes. In order to make optimal use of favourable atmospheric conditions a water vapour monitor has been deployed on Paranal, allowing for real-time decisions and the introduction of a user-defined constraint on water vapour. During the commissioning in 2012 it was found that the on-sky sensitivity of the AQUARIUS detector was significantly below expectations. Extensive testing of the detector arrays in the laboratory and on-sky enabled us to diagnose the cause for the shortcoming of the detector as excess low frequency noise (ELFN). It is inherent to the design chosen for this detector and can't be remedied by changing the detector set-up. Since this is a form of correlated noise its impact can be limited by modulating the scene recorded by the detector. After careful analysis we have implemented fast (up to 4 Hz) chopping (with field stabilization) using the secondary mirror (M2) of the VLT. The over sampling of VISIR (0.045"/pix) for a 0.3" PSF, hence reducing the background-induced current in the device, is also essential for rejecting ELFN. During commissioning the upgraded VISIR has been confirmed to be more sensitive than the old instrument (imaging) and for spectroscopy at 10 ?m a gain of a factor >6 is realized in observing efficiency. After overcoming several additional technical problems (mechanical flexure, stability of temperature regulation) VISIR is back in Science Operations since April 2015. In addition an upgrade of the IT infrastructure related to VISIR is being conducted now in order to support burst-mode operations. Science Verification of the new modes is scheduled for Feb 2016. The upgraded VISIR is a powerful instrument providing close to background limited performance for diffraction-limited observations at an 8-m telescope. It offers synergy with facilities such as ALMA, JWST, VLTI and SOFIA, while a wealth of targets is available from survey work (e.g. VISTA, WISE). In addition it will bring confirmation of the technical readiness and scientific value of several aspects of future mid-IR instrumentation at Extremely Large Telescopes. We will present several lessons learned during the project.

9908-13, Session 4

Operational performance of MOSFIRE with its cryogenic configurable slitmask unit at the W. M. Keck Observatory

Marc Kassis, W. M. Keck Observatory (United States); Ian S. McLean, Univ. of California, Los Angeles (United States); Charles C. Steidel, Keith Y. Matthews, California Institute of Technology (United States); Sean M. Adkins, W. M. Keck Observatory (United States); Jason L. Weiss, Univ. of California, Los Angeles (United States); James E. Lyke, Dwight D. Chan, W. M. Keck Observatory (United States); Peter Spanoudakis, Olivier Chételat, Christophe Meier, Philippe Schwab, Leszek Lisowski, Emmanuel Onillon, Patrick Theurillat, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland)

The Multi-Object Spectrograph for Infrared Exploration (MOSFIRE) achieved first light on the W. M. Keck Observatory's Keck I telescope on 4 April 2012, and since, MOSFIRE has become the most popular Keck I instrument, used on 40 percent of the available nights. One of the primary reasons for the instrument's popularity is that it uses a configurable slitmask unit (CSU) developed by the Centre Suisse d'Electronique et Microtechnique (CSEM SA) to isolate the light from up to 46 objects simultaneously with mask reconfiguration times taking five minutes or less. Astronomers take advantage of MOSFIRE's sensitivity and flexibility to accommodate a wide range of scientific research programs from studies of exoplanet atmospheres to those measuring redshifts of the most distant galaxies in the universe. Because it is nimble and reliable, the instrument leads the field in multi-object infrared spectroscopy.

In collaboration with the instrument development team and CSEM engineers, the Keck observatory staff look back over the last four years and identify the decisions that contributed to the success of routine and relatively trouble free nighttime operations. From our operational perspective, we present how our observing community uses the instrument including types of CSU mask configurations and their observing strategies. Sophisticated, user friendly software, coupled with orchestrated observing procedures, make MOSFIRE and the CSU efficient and robust to on-sky errors. A few operational issues such as delays in data write times, slit drift, and CSU faults contribute to lost time, observing inefficiencies, and throughput losses. Thus, we present completed - and in some cases ongoing - mitigation efforts to further improve what is already a highly efficient instrument.

9908-14, Session 4

Performance updates of HAWK-I and preparation for the commissioning of the system GRAAL+HAWK-I

Pascale Hibon, European Southern Observatory (Chile); Miska Le Louarn, European Southern Observatory (Germany); Emanuela Pompei, European Southern Observatory (Chile)

The High Acuity Wide field K-band Imager (HAWK-I) instrument is a cryogenic wide field imager operating in the wavelength range 0.8 to 2.5 microns.

It has been in operations since 2007 on the UT4 at the Very Large Telescope Observatory in seeing-limited mode. In 2017, GRound layer Adaptive optics Assisted by Lasers module (GRAAL) will be in operation and the system GRAAL + HAWKI will be commissioned. It will allow: deeper expositions for nearly point-source objects, or shorter exposition times for reaching the same magnitude, and/or deeper detection limiting magnitude. With GRAAL, HAWK-I will operate more than 80% of the time with an equivalent K-band seeing of 0.55" (instead of 0.7" without GRAAL).

We discuss here the latest updates on performance from HAWKI without Adaptive Optics (AO) and the preparation for the commissioning of the system GRAAL+HAWKI.

9908-15, Session 4

Making SPIFFI SPIFFIER: upgrade of the SPIFFI instrument for use in ERIS and performance analysis from re-commissioning

Elizabeth M. George, Helmut Feuchtgruber, Michael Hartl, Dominik Gräff, Frank Eisenhauer, Richard Davies, Alexander Buron, Heinrich Huber, Max-Planck-Institut für extraterrestrische Physik (Germany); Christian Rau, Max Planck Institut für Extraterrestrische Physik (Germany); Markus Plattner, Erich Wiezorrek, Max-Planck-Institut für extraterrestrische Physik (Germany); Harald Weisz, WEISZ Ing.-Bureau für den Maschinenbau (Germany); Paola Amico, Andreas Glindemann, George Hau, Harald Kuntschner, European Southern Observatory (Germany)

SPIFFI (SPectrometer for Infrared Faint Field Imaging) is an adaptive optics fed near-infrared imaging spectrograph that has been operational as a facility instrument for the ESO VLT as part of the SINFONI project since 2005. The instrument has been enormously scientifically productive in several areas over its 11-year lifetime, and is currently in use for several high-profile scientific programs. An upgraded version of the instrument

will be included in the new VLT AO instrument ERIS (Enhanced Resolution Imager and Spectrometer) as the IFU subsystem SPIFFIER (SPectrometer for Infrared Faint Field Imaging Enhanced Resolution).

We describe the planned changes for the upgraded instrument, which include upgrades to almost all subsystems in the instrument, including new motors and electronics, new pre-optics, new filters, new spectrometer collimator mirrors, a new diffraction grating, and a new detector. Technology developments in many areas during the last 15 years enable us to upgrade this highly successful instrument to be competitive as a second-generation instrument on the VLT and make good use of the new 4 laser guide star adaptive optics facility (AOF) on VLT UT4. These developments include modern multi-layer coatings for lenses and filters, more precise diamond turning processes in mirror manufacturing, immersion grating development, and quantum efficiency improvements in new generations of infrared detectors. We discuss the technology developments that enable us to make the SPIFFI instrument SPIFFIER, as well as the scientific performance gains expected from these upgrades.

In January 2016, we performed an “early upgrade” to some of the subsystems in the SPIFFI instrument so that ongoing scientific programs can make use of enhanced performance before ERIS arrives in 2020. In this upgrade, the optical components making up the pre-optics subsystem, bandpass filters, and spectrometer collimator mirrors were exchanged, resulting in substantial throughput and spectral resolution gains. We report the performance of SPIFFI after this early upgrade, including substantial gains in throughput and spatial and spectral resolution. Finally we show results from the re-commissioning highlighting the scientific potential for on-going and new science programs using the new capabilities of the upgraded instrument.

9908-16, Session 4

PANIC: a general purpose panoramic near-infrared camera for the Calar Alto Observatory, instrument overview and performance at telescope

Matilde Fernandez Hernandez, María Concepción Cárdenas Vázquez, Instituto de Astrofísica de Andalucía (Spain); Irene M. Ferro Rodríguez, Instituto de Astrofísica de Andalucía - CSIC (Spain); Bernhard Dorner, Max-Planck-Institut für Astronomie (Germany); Jose-Miguel Ibáñez Mengual, Instituto de Astrofísica de Andalucía (Spain)

PANIC is the new PAnoramic Near-Infrared camera for Calar Alto, a project jointly developed by the MPIA in Heidelberg, Germany, and the IAA in Granada, Spain, for the German-Spanish Astronomical Center at Calar Alto Observatory (CAHA, Almería, Spain). This new instrument is able to work at the 2.2m and 3.5m CAHA telescopes covering a field of view of 30’x30’ and 15’x15’, respectively, with a sampling of 4096x4096 pixels. It is designed for the spectral bands from Z to KS, and can be equipped with also narrow-band filters. The instrument was delivered to the observatory in fall 2014 and it was commissioned at both telescopes in spring 2015. The scientific verification of the instrument at the 2.2m and 3.5m telescopes has been successfully carried out in late 2015 and the expected camera performances comply with the scientific requirements. The camera is currently available to the astronomy community.

We describe the design, the Assembly, Integration and Verification process, the final laboratory tests and the performance of the PANIC instrument. First-light data obtained during commissioning and science verification phases are presented as well.

The laboratory final test confirmed the expected camera performances, complying with the scientific requirements. Commissioning phase on-sky has been accomplished.

PANIC works under cryogenic conditions, at about 100K, except for the detector, that works at 82K. The optical design has been optimized for the operation temperature (100K) but the mechanical design, manufacturing and assembly have been done at room temperature (300K). The mounts of the optical elements have been designed to ensure survival when temperature changes between 300K and 100K and also to position the elements at the right distances at operation temperature.

The detector, a mosaic of four 2kx2k HAWAII-2RG, and its readout electronics have been characterized and optimized. An overview of the performance will be given. The median dark current of one of the four arrays (SG4) is severely influenced by hot pixel degradation. Another array (SG3) shows signs of starting degradation. This has to be taken into account in the observation planning and the data processing.

Besides the low level software, which deals with the data acquisition at the detector level, several tools have been developed for the observation and for the data reduction. The Observation Tool (OT) is a user friendly interface for preparing the Observing Blocks, that are sets of instructions as telescope pointing, dithering patterns, filter selection or calibration observations. The Quick Look (QL) allows to keeptract of the preliminary results and it is essential to ensure that the observation plan proceeds as expected. For the scientific data reduction two pipelines have been developed: PAPI (PANIC Pipeline) for the general procedures and LEMON, for the data reduction and analysis of time series observations. The interplay of the software packages and the instrument, and the functionality of the processing pipelines, have been successfully tested during the commissioning and scientific verification.

9908-17, Session 4

The “+” for CRIRES: enabling better science at infrared wavelength and high spectral resolution at the ESO VLT

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The adaptive optics (AO) assisted CRIRES instrument is an IR (0.92 - 5.2 ?m) high-resolution spectrograph which has been in operation from 2006 to 2014 at the Very Large Telescope (VLT). CRIRES was a unique instrument, accessing a parameter space (wavelength range and spectral

resolution) which up to now was largely uncharted. In its setup, it consisted of a single-order spectrograph providing long-slit (40 arcsecond) spectroscopy with a resolving power up to R=100 000. However the setup was limited to a narrow, single-shot, spectral range of about 1/70 of the central wavelength, resulting in low observing efficiency for many modern scientific programmes requiring a broad spectral coverage. The CRIRES upgrade project, CRIRES+, transforms this VLT instrument into a cross-dispersed spectrograph to increase the simultaneously covered wavelength range by a factor of ten. A new detector focal plane array of three Hawaii 2RG detectors with 5.3 ?m cut-off wavelength will replace the existing detectors. For advanced wavelength calibration, custom-made absorption gas cells and an etalon system will be added. A spectropolarimetric unit will allow the recording of circular and linear polarized spectra. This upgrade will be supported by dedicated data reduction software allowing the community to take full advantage of the new capabilities offered by CRIRES+. CRIRES+ has now entered its assembly and integration phase and will return with all new capabilities by the beginning of 2018 to the Very Large Telescope in Chile.

9908-81, Session PS1

Introducing SpUpNIC (Spectrograph Upgrade: Newly Improved Cassegrain) on the South African Astronomical Observatory's 74-inch telescope

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We present SpUpNIC (Spectrograph Upgrade: Newly Improved Cassegrain) - the extensively upgraded Cassegrain spectrograph for the South African Astronomical Observatory's 74-inch (1.9-m) telescope. This instrument has existed in various forms over the past four decades. Initially it employed a photographic plate fed by an image intensifier, then progressed to a photon-counting system. That was followed by a pair of one-dimensional photodiode arrays known as the Reticon Photon Counting System, which was subsequently replaced by a 1798x266 SITe CCD in the mid-1990's. The latest incarnation of the spectrograph is essentially a new instrument, although certain original components - such as the slit mechanism - remain in use. The inverse-Cassegrain collimator mirrors, as well as the woefully inefficient Maksutov-Cassegrain camera optics have been replaced, as was the original CCD detector and SDSU controller. All of the moving mechanisms within the instrument (actuated by a combination of pneumatic cylinders and stepper motors) are now governed by a programmable logic controller. Thus the entire instrument is remotely configurable through the intuitive new graphical user interface run under Linux (Ubuntu) on the dedicated instrument control PC. This has also allowed time-consuming manual tasks like the Hartmann focus routine for the camera to be automated. The existing nine surface-relief diffraction gratings with various blaze wavelengths (between 340 and 1000 nm) and groove densities (ranging between 300 and 1200 lines/mm) remain available. The system also still employs a plano-convex field lens and inverse-Cassegrain collimator, but the new collimator assembly produces a larger beam to fill the grating and match the optically faster Folded-Schmidt camera design. The new camera assembly consists of a fused silica Schmidt plate, a slotted fold flat and a spherically figured primary mirror (both made of Zerodur) and a fused silica field-flattener lens that also forms the cryostat window. These optics alone have more than doubled the spectrograph throughput across the entire wavelength range by reducing the camera's central obscuration (from the slot in the fold mirror) to almost match that of the shadows from the telescope and collimator secondaries. The new CCD is a 2048x512 e2V device with 13.5-micron pixels. Being a frame-transfer chip, only half of the array is ever exposed, and the active area is usually binned (1x2) in the spatial direction to further reduce read-noise. The physically larger and more sensitive detector has extended the useful wavelength range of the spectrograph; weak copper-argon arc lines are now detectable down to 325 nm and the red end extends beyond 1100 nm. The improved performance is particularly dramatic in the blue due to the CCD being thinned and back-illuminated. The introduction of a rear-of-slit viewing camera has streamlined the acquisition process and further increased the instrument throughput. A small, pneumatically-actuated fold mirror is inserted into the beam between the collimator mirrors, allowing a Starlight Xpress Lodestar camera to image the slit from below. This facilitates accurate target positioning on the slit and optimisation of the telescope focus. An interactive quick-look data reduction tool further enhances the observing efficiency and user-friendliness of SpUpNIC.

9908-82, Session PS1

Detector upgrade of Subaru's multi-object infrared camera and spectrograph

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During the past year, the Multi-Object InfraRed Camera and Spectrograph (MOIRCS) at Subaru has undergone an upgrade of its science detectors, the housekeeping electronics and the instrument control software. This overhaul aims at increasing MOIRCS' sensitivity, observing efficiency and stability. In this presentation I will speak specifically about the installation and the alignment procedure of the two Hawaii 2RG detectors and the design of a cryogenic focus mechanism. The new detectors are expected to significantly lower the readnoise, increase its quantum efficiency, and lower the readout time. I will present results on gain, readnoise, crosstalk and latency and conclude with our mitigation strategy of alpha radiation originating from the lens coatings.

9908-83, Session PS1

Commissioning SITELLE: an imaging Fourier transform spectrometer for the Canada France Hawaii Telescope

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We describe the commissioning of the SITELLE instrument at the Canada France Hawaii Telescope (CFHT) following the pre-shipment testing and acceptance of the instrument built by ABB/Bomem at l'Université Laval in Québec, Québec, Canada. The performance of the instrument in terms of expected versus actual image quality and modulation efficiency, and the challenges of accurately determining these metrics will be presented. Early in the instrument integration problems were found obtaining clear measurements of the modulation efficiency (ME) primarily due to overfilling of the instrument pupil by the calibration illumination source placed at the collimator input. This led to further confusion concerning the fringe contrast as a function of optical path difference once the instrument was received at CFHT. Also, due to the lack of a telescope optical simulator, a clear picture of the image quality prior to shipping was difficult to obtain, and an unexpected elongation of the star images, particularly on one port of the interferometer, was observed. The resolution of these problems and mis-conceptions concerning the ME performance will be presented. We also provide a characterization of the stability of the metrology system as a function of instrument orientation, which varies considerably due to its mounting at the Cassegrain port of the CFH's equatorially mounted telescope.

9908-84, Session PS1

Faint skylines in the near-infrared: observational constraint for IFU instruments

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Night sky emission is a major issue in the study of the spectrum of distant objects. More effective methods to subtract the sky are largely used today with a new generation of optical and near-infrared spectrograph. But even using long exposures to subtract the sky, the S/N is never enough to remove completely its signature, in particular for the faint lines. Using VLT/KMOS observations, we have studied the temporal and spatial behavior of these faint skylines. We found that even after using new methods to subtract the sky, these small skylines some times still remain in the data cube. Even more, we found that the flux of these skylines changes spatially at the arcseconds scale being this still detected after combining several exposures. For the future exploitation of 3D observations, this behavior must be considered when kinematics is extracted from galaxies. We present some examples where the shape of the emission lines in the spectrum of a galaxy is affected by these faint skylines.

9908-85, Session PS1

Regaining the FORS: making optical ground-based transmission spectroscopy of exoplanets with VLT+FORS2 again possible

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Since a few years, the study of exoplanets has evolved from being purely discovery and exploratory in nature to being quite quantitative. In particular, transmission spectroscopy now allows the study of exoplanetary atmospheres. Such studies rely heavily on space-based or large ground-based facilities, as one needs to perform time-resolved, high signal-to-noise spectroscopy, with residuals at the 100 ppm level. For some time already, it was known that precision spectrophotometry with the ESO Very Large Telescope's FORS2 instrument suffered from systematic errors that made quantitative observations of planetary transits impossible. We identified the Longitudinal Atmospheric Dispersion Compensator (LADC) as the most likely culprit, and therefore embarked in a project to remove the anti-reflection coating of the LADC prisms of the twin, but no more used, FORS1 instrument and put them at the telescope. This led to a significant improvement in the depth of FORS2 zero points of 0.05 to 0.1 magnitudes, a drastic reduction in the systematic noise, and led to a renewed interest for this instrument as shown by the number of proposals submitted to perform transmission spectroscopy of exoplanets. We will present here in detail the various phases of the upgrade project, present the recommissioning results and show the level of improvement obtained in transit studies of exoplanets, with several examples. FORS2 may become the instrument of choice for ground-based transmission spectroscopy of exoplanets.

9908-86, Session PS1

Mosaic3: A red-sensitive upgrade for the prime focus camera at the Mayall 4m telescope

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The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14000 sq deg will be measured over the course of the experiment. In order to provide spectroscopic targets for the DESI survey, we are carrying out a three-band (g,r,z) imaging survey of the sky using telescopes on Kitt Peak and Cerro Tololo. At Kitt Peak National Observatory, we will use an upgraded version of the prime focus imaging camera (Mosaic3) at the Mayall 4m telescope to carry out a z-band survey of the Northern Galactic Cap at declinations > 30 deg. We have equipped an existing dewar with four 4kx4k fully depleted 500 micron-thick CCDs manufactured by the Lawrence Berkeley National Laboratory. These CCDs have the thickest active area fielded at a telescope, and increase the z-band system throughput of the system by a factor of 1.6. We are commissioning the camera and are scheduled to begin the survey observing in February, 2016. The Mosaic3 z-band survey will utilize 230 nights during the 2016 and 2017 spring observing semesters, and will be complemented by g-band and r-band observations using the Bok telescope on Kitt Peak. We describe the upgrade and performance of the Mosaic3 instrument and the scope of the northern survey.

9908-87, Session PS1

Operational challenges for astronomical instrumentation in Antarctica: results from five years of environmental monitoring of AMICA at Dome C

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The Antarctic Plateau is one of the best observing sites on Earth, especially for Infrared Astronomy. The extremely low temperatures (down to -80 C during winter), the low pressure (around 650 mbar) and the very reduced content of Precipitable Water Vapour (PWV less than 1 mm) allow indeed for a very clear and dark atmosphere, as well as for a passive, bery low instrumental background. These unique properties, however, make it very difficult to install and operate astronomical instrumentation, especially during winter. Mechanical and electronic COTS equipments cannot work at those temperatures and need to be insulated. Insulation, however, can cause an unexpected overheating inside electronic and electrical cases, because the substantial absence of humidity makes heat transfer extremely inefficient. Heat removal is also a real problem when managing heavy-duty devices, like cryocoolers, where excess power removal needs to be fast and efficient. The presence of wind (although weak) and of the related diamond ice dust phenomenon is at the origin of ice covering of surfaces and ice inlet through any opening width as small as 0.6 mm. Finally, the lack of an electrical ground in the high-plateau (3300 m and more) bases generates a wide variety of transient electrical phenomena which often make electronic instrumentation rather unstable.

The Antarctic Multiband Infrared CAmera (AMICA) is an instrument for astronomical imaging in the 2 - 25 micron wavelength range, installed at Dome C since 2010. Its automatic Environmental Control System (ECS) has been working continuously over the last 5 years, providing a large set of operational data that revealed themselves very useful in the evaluation of the instrument performance and its dependence on the environmental conditions.

This poster reports an analysis and discussion on the challenges represented by the environmental and operational conditions for an instrument working in a typical Antarctic Plateau site. Some conclusions are drawn, essentially stressing the need of a sort of “space qualification” for instruments designed for Antarctic operations.

9908-88, Session PS1

FIFI-LS diffraction grating vibration on SOFIA

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FIFI-LS (the Field Imaging Far Infrared Line Spectrometer for SOFIA) was successfully commissioned in 2014 during 6 flights on SOFIA. FIFI-LS has two symmetric channels capable of detecting infrared light in the wavelength ranges 51-120μm and 115-203μm. The infrared beam from the SOFIA telescope is diffracted by one reflective grating per channel. In each channel the observed wavelength is set by rotating the grating to a defined angular position. The wavelength span results in a total tilt angle of ±20°. The angle is constantly measured with a rotary Inductosyn transducer providing a resolution of down to 0.077 arc-seconds. The grating angle set position is reproducible within an accuracy of 4 arc-seconds. The inside of the instrument is cooled down to cryogenic temperatures in order to minimize contamination from the infrared background. Therefore, the grating, its rotating mechanisms and the measurement system need to operate at temperatures from 300K down to 6K. The positional stability of the grating is immensely important, since the position directly represents the observed wavelength. In the lab the cryostat is not exposed to any significant vibrations or accelerations. In flight vibrations of the telescope assembly are transferred to the attached cryostat and picked up by the grating assembly inside the instrument. Due to the inertial stabilization of the telescope, the power levels of the vibrations are extremely low. Nonetheless, they result in an increased movement of the grating. Due to this vibration the observed wavelength oscillates on the detector. In order to describe the dynamic behavior of the grating during flight, several tests have been performed on the commissioning flights.

Acceleration data was taken with a sensor on the outside of the instrument to quantify the vibrations FIFI-LS is exposed to in flight. Simultaneously the grating vibration itself was measured using the internal Inductosyn transducer. The acceleration sensor data reveals the vibrational spectrum and its intensity transferred through the structure of the telescope and the science instrument flange onto the instrument itself. Additionally the data taken on the inside displays the combined frequencies of the external vibrations and the natural frequencies of the grating assembly. Based on this data the impact on the image quality of FIFI-LS is further investigated.

The data enables two approaches to quantify the effect of the vibrations on the image quality, in particular the spectral resolution. First a theoretical approach was taken to calculate the oscillation of an emission line and estimate the apparent widening of this line. In a second approach lab measurements have been conducted, where the measured vibration was ‘replayed’, so the inflight grating movement was reproduced in the lab. That way, it was possible to compare emission line measurements with and without vibration directly.

The submitted paper will present the measured data and analyze the effect on the image quality of FIFI-LS.

9908-89, Session PS1

Final implementation and photon-efficiency verification of Hobby Eberly Telescope facility calibration unit

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The upgraded Hobby-Eberly Telescope (HET) has been equipped with new Facility Calibration Unit (FCU). The FCU is in support of the novel VIRUS instrument and other facility instruments and consists of the head and source box. The FCU head, connected to the source box through two liquid light guides, is attached to the bottom of the WFU Wide-Field Corrector (WFC) and can be deployed into the beam to inject calibration light through the WFC whenever calibration is needed. A set of Fresnel lenses is used in the FCU head to mimic the caustics of M1 as much as possible to re-produce the telescope’s focal plane illumination pattern.

Various imaging/non-imaging optical components are used for efficient coupling between different types of calibration line lamps and light guides. The final implementation also features the extremely uniform and bright Laser-Driven Light Source (LDLS) for spectroscopic flat field calibration. Altogether, the FCU efficiently provides calibration photons at wavelengths from 350nm to 2100nm. This paper presents the system's final hardware/software implementation and discusses its photon-efficiency relative to the on-sky spectrophotometric standard data taken through the HET's new Low-Resolution Spectrograph 2.

9908-90, Session PS1

The WIYN One Degree Imager: project update 2016

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We report on recent upgrades to the One Degree Imager (ODI) camera at the WIYN 3.5 meter telescope at the Kitt Peak Observatory. Following an initial test phase with thirteen detectors, the focal plane has been expanded by 16 new detectors, and is in shared risk science operations since the summer 2015. With currently a total of 30 Orthogonal Transfer Array CCD detectors, the total field of view is 40' x 48' on the sky. The newly added detectors underwent a design revision to address an issue where the the charge transfer efficiency is compromised under low light conditions. We discuss the imaging performance and challenges in the photometric calibration of the expanded array with multiple detector generations. In addition we describe the modification of ODI's filter change mechanism, where a degrading worm-gear drive was replaced by a chain drive. Finally, we will comment on the lessons learned from nearly three years of operating the instrument and its integration with the WIYN 3.5m telescope.

9908-92, Session PS1

Motivation for and design of a new imaging camera for the OSIRIS instrument at Keck

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The OSIRIS Instrument at W. M. Keck Observatory provides AO-assisted imaging and integral-field spectroscopy. We are providing a new imaging camera to the instrument. This new camera will improve the imaging sensitivity over a field of view not well-served by the other AO-imaging camera at WMKO, NIRC2, also improving its utility in measuring point-spread function references for IFS data reduction. We are additionally motivated to provide a stable camera useful for astrometry, such as for mapping motion of stars in the Galactic Center. We will briefly summarize the scientific and technical motivations for this new camera and discuss its telecentric OAP-based optical design, which provides a 20" x 20" field of view sampled at 10 mas/pix by a Hawaii-2RG detector. This design includes new filter wheels and improved cold pupils, and is tuned for accurate photometry and astrometry. We will also discuss aspects of the optomechanical, electronic, and software subsystems.

9908-93, Session PS1

The nuMOIRCS project: detector upgrade overview and early commissioning results

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In 2014 and 2015 the Multi-Object InfraRed Camera and Spectrograph (MOIRCS) instrument at the Subaru Telescope on Maunakea is undergoing a significant modernization and upgrade project. We are upgrading the two Hawaii2 detectors to Hawaii2-RG models, modernizing the cryogenic temperature control system, and rewriting much of the instrument control software.

The detector upgrade is replacing the Hawaii2 detectors which use the Tohoku University Focal Plane Array Controller (TUFPAC) electronics with Hawaii2-RG detectors using SIDECAR ASIC (a fully integrated FPA controller system-on-a-chip) and a SAM interface card. We expect an improvement in read noise by a factor of about 2-3 with this detector and electronics upgrade.

The cryogenic temperature control upgrade focuses on modernizing the components and making the procedures for warm up and cool down of the instrument safer. We have moved PID control loops out of software and in to Lakeshore model 336 cryogenic temperature controllers and have added interlocks on the warming systems to prevent overheating of the instrument.

Much of the instrument control software has also been re-written. This was necessitated by the different interface to the detector electronics (ASIC & SAM vs. TUFPAC) and by the desire to modernize the interface to the telescope control software which has been updated to Subaru's "Gen2" system since the time of MOIRCS construction and first light. The new software is also designed to increase reliability of operation of the instrument, decrease overheads, and be easier for night time operators and support astronomers to use.

9908-94, Session PS1

Upgraded cameras for the HESS Imaging Atmospheric Cherenkov Telescopes

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The High Energy Stereoscopic System (H.E.S.S.) is an array of five imaging atmospheric Cherenkov telescopes (IACT), sensitive to cosmic gamma rays with energies between ~30 GeV and several tens of TeV. Four of them started operations in 2003 and their 960 photomultiplier tube (PMT) cameras are currently undergoing a major upgrade, with the goals of improving the overall performance of the array and reducing the failure rate of the ageing systems. This camera upgrade assures the operation of the H.E.S.S array at its full sensitivity until and possibly beyond the end of the decade. With the exception of the PMTs, all camera components have been replaced: these include the readout and trigger electronics, the power, ventilation and pneumatic systems and the control and data acquisition software. New designs and technical solutions have been introduced: the readout electronics is based on the NECTAr analog memory chip, which sample and store the PMT signals at a frequency of 1 GHz with a dynamic range of 12 bits. In all subsystems, the control of the hardware is carried out by an FPGA coupled to an embedded ARM computer, a modular design which has proven to be very fast and reliable. The control and data acquisition software is based on modern C++ libraries such as Apache Thrift, ZMQ and Protocol buffers, offering very good performance, robustness, flexibility and ease of development. Both hardware and software have undergone extensive testing both during the development of the upgrade, and during the deployment and commissioning of the first camera, which happened in July-December 2015. The other three cameras are going to be upgraded in September 2016. This contribution describes the design, the on-field performance, the results of the tests and the lessons learned from the first upgraded H.E.S.S. camera.

9908-95, Session PS1

On-sky and laboratory tests of polarization gratings for visible and near infrared astronomy

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We report on the design, characterization and on-sky performance of a prototype slit-based spectropolarimeter instrument that employs a polarization grating (PG) optimized for operation from 0.5 to 0.9?m. PGs are a type of diffraction grating that take advantage of liquid crystal polymers to simultaneously act as a polarizing beam splitter and as a classical diffraction grating. The uniaxial birefringent properties of the liquid crystal polymers cause incident light to diffract into the m=+1 or m=-1 order, depending on its circular polarization state. With the addition of a quarter-wave plate PGs can be made sensitive to linear polarized light. Furthermore, PGs are capable of providing high diffraction efficiency (> 90%) over a very broad wavelength range. These properties make PGs ideal for spectropolarimetry and/or high throughput, broad wavelength observations for a range of astronomical objects. We have designed and constructed an instrument that uses a PG, which we have mounted on the 16" University of Toronto Campus telescope. The optical design consists of a slit, collimating optics, a rotating quarter-wave plate, a PG, camera optics and a 4k x 4k detector. We have used this instrument to carry out observations of the polarized twilight sky, as well as polarized standard stars. These observations act as a proof of concept to demonstrate the applicability of polarization gratings for astronomical applications in the visible regime. In addition, we describe our laboratory characterization work on a polarization grating designed for high diffraction efficiency between 0.6 and 1.8?m.

9908-96, Session PS1

Gemini instrument upgrade program

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Gemini is introducing a new program to produce user-motivated upgrades to our operating instruments at both Gemini sites. The objective is to simultaneously help keep the observatory current instruments competitive in the field and better serve the scientific needs of Gemini users. Part of this strategy involves launching public request of proposals for instrument upgrades of existing operational instrumentation, creating a new instrument capability at the observatory. During 2015 a first public request of proposal for small projects was launched, and in 2016 medium projects (~0.5M USD) proposals will be requested. In this work we summarise the work done and the results so far obtained within the instrument upgrade program.

9908-97, Session PS1

Commissioning the polarimetric modes of the Robert Stobie spectrograph on the Southern African Large Telescope

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The Robert Stobie Spectrograph is currently the prime spectroscopic instrument on the Southern African Large Telescope (SALT), which has been undergoing regular scientific operations since 2011. The visible beam of RSS was designed to perform polarimetry in all its modes, imaging and grating spectroscopy (with Multi Object Spectroscopy capability) from 3200 to 9000 A˚. The polarimetric field of view is 4?8 arcmin.

Initial early polarimetric commission was stalled because a coupling fluid leak developed in the polarizing beamsplitter after less than a year of operation. It was decided to redesign the beamsplitter to use a different optical couplant. This is complicated by the unusual thermal expansion properties of the calcite optic, and by the necessity of aligning the individual elements in the beamsplitter mosaic (RSS is the first to use a mosaic beamsplitter). Laboratory work selected a new couplant, a gel, Nye 451, which has been used by astronomers, including on calcite. Testing was completed with satisfactory results on a “sacrificial” calcite prism with the same geometry as an actual mosaic element. A successful assembly was performed and the beamsplitter was re-installed in SALT in mid-2015.

We describe results from the renewed commissioning to characterise polarimetry from SALT and include some early performance verification science.

9908-98, Session PS1

Data quality and reductions for the high-resolution spectrograph on the Southern African Large Telescope

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The High Resolution Spectrograph (HRS) on the Southern African Large Telescope (SALT) is a dual beam, fiber-fed echelle spectrograph providing high resolution capabilities to the SALT observing community. The instrument has four modes of operation, including low resolution (R~15000), medium resolution (R~36000), high resolution (R~65000), and a high stability mode, with each mode having a pair of object and sky fibers. The high stability mode also has a resolution of R~65000, but includes a fiber double-scrambler and the choice of either an iodine cell or simultaneous injection of thorium-argon arc light into the sky fiber to improve the wavelength calibration. The higher resolution modes employ image slicing to balance seeing limitations with the goal of achieving high resolution observations.

On-telescope commissioning of the instrument took place over a one year period between November 2013-2014 and confirmed that the instrument met specification. Full science operation followed at the end of 2014 and the spectrograph has successfully provided data for a wide range of scientific programs since. However, the scientific productivity of the HRS has been limited by two main issues: 1) a lack of data reduction software for each of the modes and 2) poor understanding of the long term stability of the instrument. These two aspects have been intertwined, since the lack of reduction software prevented regular, long-term monitoring of the instrument characteristics.

In order to solve these two issues, we embarked on several focus projects to develop tools to reduce the data and to measure the quality of the observations. The primary reduction software for HRS is the pyhrs (https://github.com/saltastro/pyhrs) software package. pyhrs is a pure python package built on several open collaboration software packages, including the astropy affiliated package ccdproc for basic CCD reductions. The spectroscopic reductions were developed based on the PySALT data reduction package. The pyhrs package includes tools for basic CCD reductions, wavelength calibration, and spectral extraction. A number of tests and observations have since been carried out to further quantify the performance of the instrument and to evaluate the quality of the data products generated by the reduction software.

An additional set of tools has recently been developed to provide feedback about the quality and stability of calibration frames such as biases, arcs and flat-fields. The different frame types were interrogated to characterise key aspects of the HRS and they are now used, in conjunction with extensive logging of environmental data, to continuously monitor the health of the instrument. HRS parameters of interest include the overscan and bias levels, the responses of the two detectors, stray light, focus, system throughput and the all-important stability of the wavelength solution. With these tools in place, regular monitoring of the HRS characteristics could be incorporated into the SALT Dashboard (see Hettlage et al. 2016).

9908-99, Session PS1

CCD system upgrading of the Kyoto3DII and integral field spectroscopic observation with the new system

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Understanding the physical mechanisms governing the formation and evolution of galaxies is one of the most important topics in modern astronomy. Spatially resolved observation such as Integral Field Spectroscopy (IFS) is able to reveal important properties of galaxies for

instance the dynamics, energetics, and ionization structures. Kyoto3DII is an optical integral field spectrograph mounted on the Subaru telescope as a PI instrument. Using IFS data provided by Kyoto3DII, we have discussed scientific issues about the activities of active galactic nuclei, starburst galaxies, and interacting galaxies, including galactic winds, as well as their effects on galactic environments and galaxy evolution. We have also investigated the lensing galaxy structure including dark matter based on gravitational lensed quasar images.

Kyoto3DII was originally mounted at the Cassegrain focus of the Subaru telescope where the wide wavelength range coverage from 3600 to 9200 angstroms was available, but the spacial resolution was limited by seeing. Thanks to the excellent optical performance and fine spatial sampling, Kyoto3DII is capable of resolving small structures. To fully exploit the spatial resolution, Kyoto3DII was moved to the Nasmyth focus after the installation of AO188, the adaptive optics (AO) system of the Subaru telescope. Since then, Kyoto3DII has provided us unique opportunities of optical IFS with AO resolution.

As AO188 can improve the spatial resolution in the red wavelength region and the blue light is reflected by a dichroic mirror to the wavefront sensor for AO correction, the important observable wavelength with Kyoto3DII becomes 6200-9200 angstroms. However, the quantum efficiency of the CCD was low in the red wavelength region because it was optimized to the non-AO observations at the Cassegrain focus.

To optimize Kyoto3DII to AO observations, we have upgraded the CCD system, including CCD, readout system, dewar, and refrigerator. We have newly installed the red-sensitive Hamamatsu fully depleted CCD, which enhances the total efficiency by a factor of ~2 in the red wavelength range. Fringes are dramatically reduced thanks to the thick silicon layer. The readout system and refrigerator help us decrease the readout noise to 3.2-3.4e-, smaller by a factor of ~3 than that of the previous system. We carried out laboratory tests related to vacuum, cooling, and readout of the CCD. We installed the new system on Kyoto3DII, and completed the optical experiments with AO188 in May 2015.

We carried out engineering and scientific observations on September 23 and 24 in 2015. We observed two standard stars (V=9.5 and 9.2) in the Natural Guide Star (NGS) mode. We also observed four galactic nuclei of nearby galaxies, two of which were observed in NGS mode, and others in the Laser Guide Star (LGS) mode. We found the spatial resolution of ~0.1 arcsec FWHM by using the 9.5 magnitude standard star in NGS mode and ~0.2 arcsec in LGS mode estimated from the galactic nucleus. We will present the performance of Kyoto3DII with the new CCD system such as total efficiency based on the observational data.

9908-101, Session PS1

A new Cassegrain calibration lamp unit for the Blanco Telescope

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The f/8 RC-Cassegrain Focus of the Blanco telescope at CTIO, hosts two new instruments: COSMOS, a multi-object spectrograph in the visible wavelength range (350-1030nm), and ARCoIRIS, a NIR cross-dispersed spectrograph featuring 6 spectral orders spanning 0.8 -2.4 microns. Here we describe a calibration lamp unit designed to deliver the required illumination at the telescope focal plane for both instruments. These requirements are: (1) an F/8 beam of light covering a spot of 100mm diameter (or 11 arcmin) for a wavelength range of ~350nm through 2.5um and (2) no saturation of flat-field calibrations for the minimal exposure times permitted by each instrument, and (3) few saturated spectral lines when using the wavelength calibration lamps for the instruments. To meet these requirements this unit contains an adjustable quartz halogen lamp for flat-field calibrations, and one hollow cathode lamp and four penray lamps for wavelength calibrations. The wavelength calibration lamps are selected to provide optimal spectral coverage for the instrument mounted and can be used individually or in sets. The device designed is based on an 8-inch diameter integrating sphere, the output of which is optimized to match the F/8 calibration input delivery system which is a refractive system based on fused-silica lenses. We describe the optical design, the opto-mechanical design, the electronic control and give results of the performance of the system.

9908-102, Session PS1

Commissioning and first observations with Wide FastCam at the Telescopio Carlos Sánchez

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The FastCam instrument platform, jointly developed by the IAC and the UPCT, allows, in real-time, acquisition, selection and storage of images with a resolution that reaches the diffraction limit of medium-sized telescopes. FastCam incorporates a specially designed software package to analyze series of tens of thousands of images in parallel with the data acquisition at the telescope.

Wide FastCam is a new instrument which, using the same software for data acquisition, do not look for lucky imaging, but fast observations in a much larger field of view. Wide FastCam uses a 1k x 1k EMCCD detector and different optics offering a ~8 arcmin FOV.

IDOM designed and supplied the optical bench integrating the main optical elements, except for the detector that was integrated at the IAC, in 2014. This paper describes the commissioning process and first observations with Wide FastCam at the Telescopio Carlos Sánchez (TCS) in the Teide Observatory.

9908-103, Session PS1

Damage and removal of the coating on the first lens of the MegaCam wide-field corrector

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The coating on the exposed surface of the 810 mm diameter first element of the MegaCam wide-field corrector at the Canada-France-Hawaii Telescope (CFHT) was found to be degraded in the fall of 2014. An investigation showed that the coating was, in fact, damaged over a large part of the exposed surface and was causing major scattering, severely degrading the performance of the instrument. The coating was subsequently removed from the lens by CFHT, restoring the majority of the instrument performance. The investigation of the degradation and the procedure used to remove the coating will be described in this paper.

9908-104, Session PS1

Upgrade of the detector in the integral field spectrograph OSIRIS at the W. M. Keck Observatory

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We present the results of the upgrade of the spectrograph detector in the integral field spectrograph, OSIRIS. OSIRIS is a near-infrared (1 to 2.5 microns) integral field spectrograph on the Keck I telescope. This instrument produces up to 3,000 spectra simultaneously over a contiguous rectangular field of view with a spectral resolution of ~3,800. OSIRIS works with the Keck Adaptive Optics system to achieve diffraction-limited spatial resolution and has four plate scales ranging from 0.02 to 0.10 arcseconds. At first light in 2005, the spectrograph portion of the instrument was equipped with a Rockwell Hawaii-2 detector. We have now upgraded this to a Teledyne Hawaii-2RG (H2RG) with lower read noise, lower dark current, and higher quantum efficiency. In addition to the upgraded detector, we also mounted the detector head on a linear stage, allowing the position of the detector to be accurately adjusted along the optical path when the instrument is at cryogenic temperatures (~80 K).

9908-105, Session PS1

Optical design of the slit-viewing camera for the NIRSPEC upgrade

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NIRSPEC is a 1-5 um medium and high-resolution echelle spectrograph for the Keck II telescope, currently being upgraded to replace detectors and electronics in the spectrograph and slit-viewing camera (SCAM). The existing SCAM design is limited to the 1-2.5 um regime and optimized for the PICNIC 256x256 40 um pixel array. The upgrade to a Teledyne H1RG 1024x1024 18 um pixel array will allow imaging of the slit from 1-5 um, increasing observing efficiency in the L and M bands. The extension of SCAM's wavelength coverage and significant decrease of the pixel size require a redesign of the SCAM system and allow for re-optimization of pixel sampling and field of view. We present opto-mechanical modeling of the SCAM design, optimized for the replacement detector. We discuss lens choices, anti-reflective coatings, and the addition of blocking filters to mitigate the high background levels in the thermal infrared.

9908-106, Session PS1

On-sky commissioning of Hamamatsu CCDs in GMOS-S

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GMOS-S has been recently upgraded with Hamamatsu deep depletion CCDs replacing the original EEV detector array. The new CCDs have superior quantum efficiency (QE) at wavelengths longer than 680nm, with significant sensitivity extending beyond 1 micron. Furthermore, the fringing level in GMOS-S data is now much lower due to the much thicker CCDs, further improving delivered sensitivity above that afforded by quantum efficiency alone. Soon after the Hamamatsu CCDs were installed in June 2014, some issues were noticed that impacted some science programs. In particular, saturated stars or spectral features created bands of artifacts on the amplifier containing the saturated features. A bright glowing pixel rendered one of the amplifiers essentially useless for one of the amplifiers in long exposures. In addition, an intermittent noise issue caused significant problems for observations using the Nod & Shuffle mode. In October 2015 the ARC controller electronics were upgraded and a cable was replaced, and since then GMOS-S has again been taking science data with the Hamamatsu detectors with no sign of these previous unfortunate limitations. We present the results of the GMOS-S on-sky commissioning of the Hamamatsu detector array, and provide an update on the status of the GMOS-N portion of the project.

9908-107, Session PS1

Easy mounting interface for compact instruments at TNG

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TNG is able to offer an F/11 Nasmyth focal station with an easy mount for small devices or compact instruments. One or more of the 5 slit masks at the focal plane of the LRS spectrograph can be removed in few minutes from the selector stage. A FoV of 9x9arcmin^2 is available and a small instrument can be mounted on a mechanical interface of 240x120mm on the sides. The size of the instrument along the optical axis is limited by the support of the collimation lens of the spectrograph.

This solution has already been used successfully for small devices like a CCD camera or a SH sensor and a compact instrument consisting of 3 Hamamatsu photometers. From 2016 one of the slits position will permanently host the folding optical relay for the GIARPS Instrument. This interface is an opportunity to test new instruments, prototypes or demonstrators in a not invasive or time consuming way at a 4m class telescope.

9908-108, Session PS1

A method for reducing atmospheric noise without chopping for ground-based mid-infrared observations

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Fluctuation of atmospheric radiation causes serious noise in ground-based mid-infrared observations, especially at 20-micron or longer wavelengths. Chopping is a common and conventional technique to estimate the atmospheric emission at the time of imaging, by means of taking short exposures to the object and the sky alternately. This is effective if the chopping frequency is higher than the typical timescale of the sky turbulence (>2 Hz). However such high frequency chopping increases the overhead time and decreases the observing efficiency.

The fact that the chopping technique can reduce the atmospheric turbulence noise indicates that the difference of atmospheric emission between a few ten arcseconds is negligible in short time scale. Therefore the spatial structure of the atmospheric emission could be expressed as low-order models. Such approaches to reproduce the sky frame have been tried by some groups, but failed in making sufficient models with accuracy better than 1 part in 10,000.

We have found a method for estimating the sky frame empirically and removing the atmospheric noise effectively. In this method, a “good sky frame” is defined as the frame that has the same spatial pattern as the target frame. Since the atmospheric emission has not complicated spatial patterns and varies continuously, the good sky frame can be composed by the superposition of several sky frames. Specifically, we calculate weighted average coefficients that minimize the standard deviation of blank sky region on the sky-subtracted images. The coefficients can be found by solving an equation with the method of Lagrange multiplier. This is named as “weighting average method”.

The verification of this method has been conducted with applying to the actual observation data of MAX38 which is mounted on miniTAO 1-m telescope. The observed data of a standard star HD168625 has been processed in two ways. One is a conventional reduction; a simply averaged image of the off-source frames was subtracted from that of the on-source images. Another one is our new method, using only the on-source frames and weighted averaging instead of the simple averaging. The results clearly show that the residual patterns were reduced by the weighted average method. This is quite meaningful since the residual patterns by the atmospheric turbulence can be reduced without the chopping technique. This is very useful not only for improving the observing efficiency but also for taking images of extended objects larger than the chopping throw.

In this paper we will report the details of this weighting average method and demonstrate its performance against the practical observing data.

9908-109, Session PS1

SOFIA’s secondary mirror assembly: in-flight performance and control approach

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The Stratospheric Observatory for Infrared Astronomy (SOFIA) is a 2.5m infrared telescope built into a Boeing 747 SP. In 2014 SOFIA reached its Full Operational Capability milestone and nowadays takes off about three times a week to observe the infrared sky from altitudes above most of the atmosphere’s water vapor content.

An actively controlled 352mm SiC-Secondary Mirror is used for infrared chopping with peak-to-peak amplitudes of up to 10 arcmin and chop frequencies of up to 20Hz and also as actuator for fast pointing corrections.

The Swiss-made Secondary Mirror Mechanism (SMM) is a complex and highly integrated and compact flexure based mechanism that has been performing with remarkable reliability during recent years. Above mentioned capabilities are provided by the Tilt Chopper Mechanism (TCM) which is one of the two stages of the SMM. In addition the SMM it is also used to establish a collimated telescope and to adjust the telescope focus depending on the environmental temperature which ranges from about 40°C at takeoff in Palmdale, CA to about 40°C in the stratosphere. This is achieved with the Focus Center Mechanism (FCM) which is the base stage of the SMM on which the TCM is situated.

Initially the TCMwas affected by strong vibrations at about 300Hz which led to unacceptable image smearing.

After some adjustments to the PID-type controller it was finally decided to develop a completely new control algorithm in state space. This pole placement controller matches the closed loop system poles to those of a

Bessel filter with a corner frequency of 120Hz for optimal square wave behavior. To reduce noise present on the position sensors and to estimate the velocity a simple static gain Kalman Filter was designed and implemented.

A system inherent delay is incorporated in the Kalman filter design and measures were applied to counteract the actuators’ hysteresis. For better performance over the full operational temperature range and to represent an amplitude dependent non-linearity the underlying model adapts in real-time to those two parameters. This highly specialized controller was developed over the course of years and only the final design is introduced here.

The main intention of this paper is to present the currently achieved performance of the SOFIA chopper over the full amplitude, frequency, and temperature range. Therefore a range of data gathered during in-flight tests aboard SOFIA are displayed and explained. The SMM’s three main performance parameters are the transition times between two chop positions, the stability of the Secondary Mirror when exposed to the low pressures, low temperatures, aerodynamic, and aeroacoustic excitations present when the SOFIA observatory operates in the stratosphere at speeds of up to 850 km/h, and finally the closed-loop bandwidth available for fast pointing corrections.

9908-110, Session PS1

Development of the FPI+ as facility science instrument for SOFIA cycle four observations

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The Stratospheric Observatory for Infrared Astronomy (SOFIA) is a heavily modified Boeing 747SP aircraft, accommodating a 2.7m infrared telescope. This airborne observation platform takes astronomers to flight altitudes of up to 13.7 km (45,000ft) and therefore allows an unobstructed view of the infrared universe at wavelengths between 0.3 μm and 1600 μm.

SOFIA is currently completing its third cycle of observations and utilizes seven different imaging and spectroscopic science instruments. New instruments for SOFIA’s cycle 4 observations, starting in February of 2016, are the High-resolution Airborne Wideband Camera-plus (HAWC+) and the Focal Plane Imager (FPI+). The latter is an integral part of the telescope assembly and is used on every SOFIA flight to ensure precise tracking on the desired targets. The FPI+ will be used as a visual-light photometer in its role as facility science instrument.

Since the upgrade of the FPI camera and electronics in 2013, it uses a thermoelectrically cooled science grade EMCCD sensor inside a commercial-off-the-shelf Andor camera. The back-illuminated sensor has a peak quantum efficiency of ~95% and the dark current is as low as 0.01 e-/pix/sec. With this new hardware the telescope has successfully tracked on 16th magnitude stars and thus the sky coverage, e.g. the areas of sky that have suitable tracking stars, has increased to 99%.

Before its use as an integrated tracking imager, the same type of camera has been used as a standalone diagnostic tool to analyze the telescope pointing stability at frequencies up to 200 Hz (imaging with 400 fps). These measurements helped to improve the telescope pointing control algorithms and therefore reduce the image jitter in the focal plane. Science instruments benefit from this improvement with smaller image sizes for longer exposure times.

The FPI has also been used to support astronomical observations like stellar occultations by the dwarf planet Pluto and a number of exoplanet transits. Especially the observation of the occultation events benefit from the high camera sensitivity, fast readout capability and the low read noise and it was possible to achieve high time resolution on the photometric light curves.

This paper will give an overview of the development from the standalone diagnostic camera to the upgraded guiding/tracking camera, fully integrated into the telescope, while still offering the diagnostic capabilities and finally to the use as a facility science instrument on SOFIA.

9908-18, Session 5

The Gemini Planet Imager: first years on the sky *(Invited Paper)*

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The Gemini Planet Imager (GPI) is first facility-class high-contrast imaging system operational on the Gemini South telescope. It combines a high-order adaptive optics system with an apodized-pupil Lyot coronagraph and a low spectral resolution integral field spectrograph. After first light in late 2013, GPI began science operations. The GPI Exoplanet Survey has observed 150 stars and produced a large database of instrument performance metrics such as contrast, both in individual images and after post processing, together with adaptive optics telemetry and environmental conditions such as tau0 and r0, allowing us to explore the factors determining contrast. We present an evaluation of system performance after 2 and a half years on the sky, with science highlights, lessons learned, and areas for potential future improvement.

9908-19, Session 5

SPHERE: on-sky results

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SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research in Europe) is a second-generation instrument for the ESO Very Large Telescope (VLT) dedicated to the direct detection and spectral characterization of giant extra-solar planets, which is one of the most exciting but also one of the most challenging areas in modern astronomy due to the very large contrast between the host star and the planet at very small angular separations. SPHERE combines an extreme adaptive optics system, various coronagraphic devices and a suite of focal instruments providing imaging, integral field spectroscopy and polarimetry capabilities in the visible and near-infrared spectral ranges. After 10 years of development, SPHERE obtained its first light in May 2014, has been successfully commissioned at the VLT during the past year and is now offered to the community since April 2015. We will give an overview of the science objectives and main instrument features, review the performance achieved during the commissioning period and present some highlights of the first science results.

9908-20, Session 5

Very high-contrast performances status with the infrared differential imager and spectrograph for SPHERE

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SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research) is a second-generation instrument for the VLT, optimized for very high-contrast imaging around bright stars. Its primary goal is the detection and characterization of new giant planets around nearby stars, together with the observation of early planetary systems and disks. The Infrared Dual Imager and Spectrograph (IRDIS), one of the three SPHERE subsystems, providing dual-band imaging in the near-infrared, among with other observing modes such as long slit spectroscopy, classical imaging and infrared polarimetry, is able to achieve extremely high contrast with the help of extreme-AO turbulence compensation, coronography, exceptional image quality, very accurate calibration strategies and advanced data processing. The SPHERE garanteed time Survey observations has started early 2015, and so far approximately 150 stars have already been observed. IRDIS achieves the sensitivity and resolution compatible with detection planetary companions with separations of 0.2" to 1" around a very large set of selected stars. We will review the high contrast performances achieved at this stage of the GTO observations with IRDIS/SPHERE and we will highlight the main results obtained during this first year of operation.

9908-21, Session 5

AOLI: near-diffraction limited imaging in the visible on large ground-based telescopes

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AOLI (Adaptive Optics Lucky Imager) is the first of a new class of instruments intended to deliver near-diffraction limited images in the visible on 4-10 meter class ground-based telescopes. It builds on the experience gained on the Palomar 5 m telescope that delivered images in the visible with a resolution approximately 3 times that of the Hubble space telescope. AOLI uses a combination of Lucky Imaging with an array of photon counting EMCCDs, together with low order adaptive optics. A key requirement for AOLI is the ability to work with very faint natural guide stars over much of the sky. A novel design of wavefront sensor uses a near-pupil plane curvature sensor that allows the use of very faint natural guide stars. At present, AOLI is configured to use a geometric wavefront sensor which gives relatively high order correction with bright reference stars but even with very faint (~17m in I band) will allow significant low order correction. This allows the system to be operated over much of the sky even at high galactic latitudes. Such an instrument will be key to providing extremely high resolution images in the visible in the post-Hubble era. This paper will report on the current status of the instrument as well as early results from the first observing run on the WHT 4.2 m telescope on La Palma. Future plans envisage the transfer of AOLI to the GTC 10.5 m telescope on La Palma which should deliver images with a resolution in the region of 20 milliarcseconds in I band under median seeing conditions.

9908-22, Session 5

LINC-NIRVANA at LBT: final preparations for first light

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We present an update on LINC-NIRVANA (LN), an innovative, high-resolution infrared imager for the Large Binocular Telescope (LBT). LN employs Multi-Conjugate Adaptive Optics (MCAO) to deliver a diffraction-limited field of view two arcminutes across, although the current science camera field is considerably smaller. LINC-NIRVANA actually has two identical MCAO systems, one for each of the 8.4 m mirrors of the LBT. The instrument accepts light from both telescopes and is designed for incoherent overlap or interferometric beam combination with off-axis fringe tracking. When implemented, the latter mode will provide panoramic Fizeau-mode imagery over much of the sky with the 10 mas spatial resolution corresponding to a 23-meter diameter telescope.

Since the last SPIE, the LINC-NIRVANA team has completed lab integration, system level tests, and preparation of the early science plan. This effort culminated in Preliminary Acceptance Europe in May 2015, followed by several months of final testing, disassembly and shipping. We report on these efforts with a focus on laboratory performance demonstration and testing of the various AO loops in the lab and on-sky.

LINC-NIRVANA is now in the mountain laboratory at the Large Binocular Telescope undergoing final alignment and testing prior to first on-sky measurements in Fall 2016. An initial craning and fit-test in November 2015 placed the instrument on the telescope itself within the capture range of the LBT bulk optics. Transportation and installation of such a large, complex instrument involved 10 shipping containers holding more than 35 tonnes of hardware. Executing the move from Europe to Arizona presented a number of challenges. We report on several technical and logistical issues that are very relevant to the next generation of extremely large telescopes.

Bringing LINC-NIRVANA into operation will involve a hierarchical sequence of internal instrument alignment, followed by alignment of the telescope, and finally on-sky verification and commissioning. We report on this strategy and its interaction with the Early Science plan, which has been designed to maximize the astronomical return of the instrument during this complicated phase between installation and routine operations.

9908-23, Session 6

Laboratory testing and commissioning of the CHARIS integral field spectrograph

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The Coronagraphic High Angular Resolution Imaging Spectrograph (CHARIS) is an integral field spectrograph (IFS) that has been built for the Subaru telescope. CHARIS has two imaging modes; the ‘high-resolution’ mode is R82, R69, and R82 in J, H, and K bands respectively while the ‘low-resolution’ discovery mode uses a second ‘low-resolution’ prism with R19 spanning 1.15-2.37 microns (J+H+K bands). The discovery mode is meant to augment the low inner working angle of the Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) adaptive optics system, which feeds CHARIS a coronagraphic image. The goal is to detect and characterize brown dwarfs and hot Jovian planets down to contrasts five orders of magnitude dimmer than their parent star at an inner working angle as low as 80 milliarcseconds. CHARIS constrains spectral crosstalk through several key aspects of the optical design. Additionally, the repeatability of alignment of certain optical components is critical to the calibrations required for the data pipeline. Specifically the relative alignment of the lenslet array, prism, and detector must be highly stable and repeatable between imaging modes. We report on the measured repeatability and stability of these mechanisms, measurements of spectral crosstalk in the instrument, and the propagation of these errors through the data pipeline. Another key design feature of CHARIS is the prism, which pairs Barium Fluoride with Ohara L-BBH2 high index glass. The dispersion of the prism is significantly more uniform than other glass choices, and the CHARIS prisms represent the first NIR astronomical instrument that uses L-BBH2 as the high index material. This material choice was key to the utility of the discovery mode, so significant efforts were put into cryogenic characterization of the material. The final performance of the prism assemblies in their operating environment is described in detail. The spectrograph is going through final alignment, cryogenic cycling, and is being delivered to the Subaru telescope in April 2016. This paper is a report on the laboratory performance of the spectrograph, and its current status in the commissioning process so that observers will better understand the instrument capabilities. We will also discuss the lessons learned during the testing process and their impact on future high-contrast imaging spectrographs for wavefront control.

9908-24, Session 6

FRIDA: diffraction-limited imaging and integral-field spectroscopy for the GTC

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FRIDA is a diffraction-limited imager and integral-field spectrometer that is being built for the adaptive-optics focus of the Gran Telescopio Canarias. FRIDA has been designed and is being built as a collaborative project between institutions from México, Spain and the USA. In imaging mode FRIDA will provide scales of 0.010, 0.020 and 0.040 arcsec/pixel and in IFS mode spectral resolutions of 1000, 4000 and 30,000. FRIDA is starting systems integration and is scheduled to complete fully integrated system tests at the laboratory by the end of 2017 and be delivered to GTC shortly after. In this contribution we present a summary of its design, fabrication, current status and potential scientific applications.

9908-25, Session 6

Three years of harvest with the vector vortex coronagraph in the thermal infrared

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Vector vortex coronagraphy is one of the most promising techniques to reach the long-term goal of imaging Earth-like exoplanets in the habitable zone of nearby main sequence stars. In their most basic version, vector vortex coronagraphs (VVC) are based on the use of a vortex phase mask (helical phase ramp) in a focal plane, followed by a Lyot stop in a downstream pupil plane. They feature a very small inner working angle, a high throughput, a 360° degree discovery space, and can work on broadband filters. For about 10 years, our team has been developing an implementation of the vortex phase mask based on concentric sub-wavelength gratings, referred to as the Annular Groove Phase Mask (AGPM). Sub-wavelength gratings produce form birefringence, which we use to synthesize a helical phase ramp for the two polarization states of light separately. Synthetic diamond was chosen as an appropriate material to produce these devices, thanks to its superb optical, mechanical and thermal properties. Because the grating period scales with the observing wavelength, we have started for technical reasons with the production of AGPMs for the thermal infrared, which ranges between 3 and 13 microns. First science-grade AGPMs were produced in 2012, and were soon installed on state-of-the-art infrared cameras, including VLT/NACO and VLT/VISIR (installation in 2012), LBT/LMIRCam (2013), and Keck/NIRC2 (2015). Here, we report on the first scientific results and on-sky performance of our thermal infrared vortex coronagraphs on these four cameras, and on the lessons learned from the first three years of on-sky operations (2013-2016). More specifically, we will describe how the vortex coronagraph performance depends on the design of the various telescopes and instruments, and on wave front quality delivered by the adaptive optics system (where available). We will discuss the efforts that have been undertaken to streamline the observing sequence, including the acquisition of the star and the chopping/nodding needs, as well as the implementation of our real-time pointing algorithm based on the science images. The importance of non-common path aberrations will be illustrated. Finally, we will discuss the perspectives for AGPMs, including operations at shorter wavelengths, adaptation to higher topological charges for reduced sensitivity to pointing errors, combination with optimal pupil-plane apodization, and applications on future extremely large telescopes.

9908-27, Session 6

Efficiently feeding single-mode fiber photonic spectrographs with an extreme adaptive optics system: on-sky characterization and preliminary spectroscopy

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Extreme adaptive optics systems enabling >90% Strehl ratios in the H band are now operational. Although primarily designed for high-contrast imaging, the compact point-spread-function and flat wavefront are also ideal for coupling into single-mode photonic devices efficiently. Photonic technologies operate at the diffraction-limit and so although they offer

numerous advanced functionalities like spatial and spectral filtering, they have thus far been greatly overlooked in next generation instrumentation owing to the difficulty with efficiently coupling light into them.

To address this concern we have built a fiber injection behind the extreme AO system inside the SCExAO instrument at the Subaru Telescope. The system includes custom pupil apodization optics which reformat the light in order to eliminate the 82% coupling efficiency limit between an Airy pattern and a Gaussian beam, a long standing problem when coupling from a telescope. We utilize the low order wavefront sensor in SCExAO which offers sub-millarcsecond pointing to keep the beam well registered with respect to the core of the fiber. We show that in laboratory characterization with a turbulence simulator we can achieve coupling efficiencies approaching 80% in the H-band when the wavefront error is in the extreme AO correction regime.

To take advantage of this highly efficient fiber feed, we utilize a compact spectrograph based on an arrayed waveguide grating (AWG). This is a spectrograph contained on a single photonic chip measuring only several square centimeters in size. The single mode fiber is bonded directly to the chip and the output reimaged on to a detector with two lenses and a prism as a cross-dispersor. This simple and compact spectrograph offers a R~3000-5000 in the J/H bands and has a very high transmission of 44+/-3%.

In this body of work we present the on-sky results and full characterization of our fiber injection setup behind the ExAO system in SCExAO in the NIR. In addition we demonstrate the on-sky performance of the extremely efficient AWG-based photonic spectrograph and show numerous on-sky spectra collected of calibrator and post AGB stars.

9908-28, Session 6

The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII): towards the first flight

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The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII) features two 50-cm collectors separated by 8 meters and a cryogenic beam-combining instrument at the center of a carbon fiber and steel truss. The instrument will enable spatially-resolved spectroscopy of nearby, bright star-forming clusters. We should be able to reach 0.5-1" spatial resolution between 30 and 90 microns. We will present the context for the instrument, as well as its significance in NASA's efforts to achieve higher angular resolution at all wavelengths.

The SPIE conference will happen 1 month before the payload needs to be ready to ship for the launch site in Fort Sumner, New Mexico, USA, in order to fly during the Fall 2016 campaign. We will report on some key design aspects of the payload, that were chosen to mitigate major challenges. We will discuss technical topics among the following: thermal design and materials selection, aluminum optics manufacturing, alignment procedures and techniques, detector design, momentum control mechanisms, flight electronics, attitude estimation and control, and embedded software.

We will present recent results from the alignment and testing campaign in all of these various areas.

9908-29, Session 7

Opening a new window on the southern stars for less money: PAIX the first Antarctica polar mission photometer *(Invited Paper)*

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Stellar pulsations and Asteroseismogy are currently among the fundamental techniques to improve our understanding of the internal structure of stars and the hydrodynamics of their atmosphere. On the observational side, progress is limited by the data accuracy needed to detect numerous modes of oscillations with small amplitudes and by the discontinuous nature of typical ground-based data strings which often introduce ambiguities in the determination of oscillation frequencies. Space missions such as MOST, CoRoT and KEPLER enable to overcome both difficulties, and indeed have considerably enhanced the scope of pulsation and Asteroseismology methods. However, the outcome of the space missions on the stellar oscillation fields shows large gaps in terms of flexibility during the observing runs, the choice of targets, the repair of failures and the inexorable high costs. Now the time has come to implement a new way to study the stellar oscillations with long uninterrupted and continuous observations over 150 days from the ground. South polar site –Dome Charlie– the great image quality and the high time coverage with PAIX -Photometer AntarctIca eXtinction-. This programme is made of the low–cost commercial components, and achieves astrophysical measurement time-series of stellar pulsation fields, challenging photometry from space. PAIX gives new insight to cope with unresolved stellar enigma and stellar oscillation challenges and offers a great opportunity to benefit from an access to one of the best astronomical site on Earth –Dome Charlie– where the seeing reaches a median value of 1 arcsec during the polar night. PAIX is attached to the Cassegrain focus of a 40-cm Ritchey-Chrétien optical telescope, with a F/D ratio of 10, located at Dome C in the open field, without any shelter, installed at ice level. PAIX challenges space telescopes and even has more advantages than CoRoT and KEPLER in observing in UBVRI bands and then collecting multicolor light curves simultaneously of several targets within the same 12.4 x 8.3 arcmin field of view.

PAIX has been antarctized to run under extreme weather conditions with temperatures as low as -80 deg.C, and has been robotized, designed and built by PaixTeam whose operating headquarters are located at Universié de Nice Sophia–Antipolis and Observatoire de la Côte d'Azur.

In this talk, we describe the first polar mission PAIX -Photometer AntarctIca eXtinction- and the first outcome of stellar pulsation from the heart Antarctica during 1 polar night. We briefly discuss our new results and perspectives on the polar instrumentation development and stellar evolution from Antarctica, especially the connection between temporal hydrodynamic phenomena and cyclic modulations and how PAIX challenges space telescopes and even has more advantages in observing in UBVRI bands and then collecting multicolor photometric measurements. Finally, we highlight the impact of PAIX -the robotic Antarctica photometer- on the stellar pulsation and evolution study.

9908-30, Session 7

Six winters of photometry from Dome C, Antarctica: challenges, improvements, and results from the ASTEP experiment

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ASTEP (Antarctica Search for Transiting ExoPlanets) is a pilot project that aims at searching and characterizing transiting exoplanets from Dome C in Antarctica and to qualify this site for photometry in the visible. The uninterrupted night during the Antarctic winter and the favorable atmospheric conditions are highly beneficial to time-series photometric observations. Two instruments were installed at Dome C and ran during the winters between 2008 and 2013. The first instrument, ASTEP South, is a fixed 10 cm lens and CCD camera system placed in a thermalized box pointing continuously towards a 3.88° x 3.88° field of view centered on the celestial South pole. The second instrument, ASTEP400, is a pointable 40 cm Newton telescope with a 1° x 1° field of view equipped with a science CCD camera and a guiding system, designed and built by our team to achieve high precision photometry under the extreme conditions of the Antarctic winter. The analysis of the data collected by ASTEP South and ASTEP400 over four winters each, with two overlapping winters, is nearly complete. In this paper, we present the technical challenges, solutions, and limitations of these instruments in light of the quality of the extracted lightcurves. By observing a single field continuously during four winters, ASTEP South provides a unique and uniform database that allows us to monitor the photometric quality as a function of meteorological and instrumental parameters. On the other hand, pointing the ASTEP400 telescope at different fields of view over the winters yields precious information on operating and automatizing an optical telescope in Antarctica. We investigate correlations between instrumental and external parameters in order to understand the behavior of the instruments. We detail issues and improvements made over the years and their impact on the operations and quality of the data. We show that instruments installed on the ice are stable and have a negligible motion over several winters. We show that with very large and rapid fluctuations of the ambient temperature, thermalizing and controlling the temperatures at various locations on the instruments is crucial to achieve photometric stability. We show that seeing fluctuations at the ground level strongly affect the photometry, and we suggest ways to overcome this issue. We demonstrate the quality of Dome C for photometry in the visible from the lightcurves themselves using the large ASTEP South database. We present logistical improvements made to the Concordia station during these years that helped running the ASTEP experiment and will be crucial for future telescopes installed at this location. Finally, we summarize the observation strategies and the key scientific results obtained by the ASTEP project. These results demonstrate the quality of Dome C for transiting exoplanet observations and for photometry in general, and will help identify the most relevant science cases for future instruments at Dome C. Based on the ASTEP experience, we also suggest ways to fully exploit the potential of this unique observing site, focusing on exoplanet science. Overall, results from the ASTEP experiment will serve as a basis to design and operate future optical and near infrared telescopes in Antarctica.

9908-31, Session 7

GLUT: a balloon-borne high-cadence UV monitoring telescope for supernova shock breakouts and exoplanet atmospheres

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(300 mm primary) on a series of long-duration high-altitude balloon flights. The wide field camera (7 square degrees) will perform high cadence (10-120 second rolling integrations) each "night" for campaign durations of three to six months. The principle science mission is the early-time detection of supernova shock-breakout at near-UV wavelengths. Additionally, early design analysis has shown the system is also able to probe the atmospheric composition of exoplanet atmospheres through the combination of UV transit measurements with ground-based measurements at longer wavelengths. In this presentation we will present the suitability of a long-duration balloon platform for such a mission, focusing on the necessary mission requirements (sensitivity, sky coverage, cadence etc.) and the available platform suitability. Particular attention is payed to platform stability, and, the accessible wavelength range as a function of flight altitude and atmospheric transmission.

9908-32, Session 7

The Evryscope: developing the cameras for the first full-sky gigapixel-scale telescope

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The Evryscope is a new type of telescope which covers the entire accessible sky in each exposure. Its 8000-square-degree field-of-view 691 MPix telescope is sensitive to exoplanet transits and other short

timescale events not discernible from existing large-sky-area astronomical surveys. The telescope, which places 24 separate individual telescopes into a common mount which tracks the entire accessible sky with only one moving part, is building 1%-precision, many-year-length, high- cadence light curves for every accessible object brighter than ~16th magnitude. The camera readout times are short enough to provide near-continuous observing, with a 97% survey time efficiency. The Evryscope has the largest survey grasp of any current ground-based survey, and is the only existing survey within an order of magnitude of LSST's étendue. We deployed the Evryscope, funded by NSF/ATI, at CTIO in late May 2015.

We will present the overall instrument design, in particular detailing the design of our new "Robotilter" camera units, which provide robotic four-degree-of-freedom image quality optimization using low-cost and robust components suitable for our 24-camera deployment. The Evryscope now has over 100 actuators, all under full robotic control, and we will present the challenges and solutions for operating such a complex instrument.

The Evryscope is producing a night-by-night two-minute cadence record of all Southern sky events down to at least 16th magnitude, enabling searches for rapid-timescale variability phenomena ranging from exoplanet transits to gamma-ray-bursts. The system's enormous field of view allows us to simultaneously monitor very large numbers of targets that would otherwise require individual targeting by dedicated telescopes. The Evryscope is sensitive to transiting exoplanets around white dwarfs, M-dwarfs, and the nearest and brightest stars, and is the first to be able to rapidly monitor most of the sky for nearby-star microlensing events. The Evryscope obtains precise and high-cadence eclipse timing for all Southern eclipsing binaries brighter than 16th magnitude, simultaneously monitors a host of compact-object pulsation and accretion phenomena, and is searching for young stars by their photometric activity. When relatively rare transients events occur, such as gamma-ray bursts (GRBs), nearby supernovae, or even gravitational wave detections from the Advanced LIGO/Virgo network, the telescope will return minute-by-minute light curves and upper limits without needing pointing towards the event as it occurs. By co-adding images, the system will reach V?18 in one-hour integrations, enabling the monitoring of faint objects. Finally, by recording all data, the Evryscope will be able to provide pre-event imaging at two-minute cadence for bright transients and variable objects, enabling the first high-cadence searches for optical variability before, during and after rapid events detected at other wavelengths. The system has already produced hundreds of thousands of images and over 20TB of data, is meeting our image quality goals, and is achieving at least 5 mmag photometric precision in light curves. We will also present our plans for further development: a Polar Evryscope which takes advantage of the continuous winter darkness in the Arctic and Antarctic to achieve much higher detection efficiency for long-period exoplanets, and larger-aperture systems which would be capable of rapidly detecting faint extragalactic events.

9908-26, Session PS2

Near-Infrared Imaging Spectro-polarimeter (NIRIS) of the New Solar Telescope at Big Bear Solar Observatory

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Near InfraRed Imaging Spectro-polarimeter (NIRIS) has been outfitted to the 1.6-meter New Solar Telescope (NST) in at Big Bear Solar Observatory (BBSO) which is the largest aperture solar telescope. NIRIS offers unprecedented high resolution spectroscopic and polarimetric imaging data of the solar atmosphere from the deepest photosphere through the base of the corona. With the aid of the BBSO adaptive optics (AO) system, the spatial resolution is close to the diffraction limit of the NST. The spectroscopic cadence reaches one second, while polarimetric measurements, including Stokes I, Q, U, V profiles, remain at a better than 20 s cadence. Polarization sensitivity is expectedto be reach ? 10^{?4}Ic. NIRIS covers a broad spectral range from 1.0 to 1.7 micron, with particular attention to two unique spectral lines: the FeI 1565 nm doublet has already proven to be the most sensitive to Zeeman effect for probing the magnetic field in the deepest photosphere; the HeI 1083 nm multiplet is one of the best currently available diagnostic of upper chromospheric magnetic fields that allows one to map the vector field at the base of the corona. NIRIS is built on dual Fabry-Pérot Interferometers (FPIs), each of which has an aperture of 100 mm. The larger aperture of FPIs allows the available field-of-view up to 85" with a spectral power of ? 10^5.

9908-111, Session PS2

Avalanche photo diodes in the observatory environment: lucky imaging at 1-2.5 microns

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The recent availability of large format near-infrared detectors with sub-election readout noise is revolutionising our approach to wavefront sensing for adaptive-optics. However, as with all near-infrared detector technologies, challenges exist in moving from the comfort of the laboratory test-bench into the harsh reality of the observatory environment. As part of the broader adaptive optics program for the GMT, we are developing a near-infrared Lucky Imaging camera for operational deployment at the ANU 2.3m telescope at Siding Spring Observatory. The system provides an ideal test-bed for the rapidly evolving Selex/SAPHIRA eAPD technology while providing scientific imaging at angular resolution rivalling HST. We will present our Lucky Imaging system, with a focus on the development of components fundamental to the future of near-infrared wavefront sensing for ELT instruments such as the GMT integral field spectrograph, GMTIFS. This includes the necessary cryogenic amplification to minimise pick-up noise, and the capabilities of the eAPD technology for photon counting at high frame-rates.

9908-112, Session PS2

Final integration and alignment of LINC-NIRVANA

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The LBT (Large Binocular Telescope), located at about 3200m in Mount Graham (Tucson, Arizona) is an innovative project undertaken by institutions from Europe and USA. LINC-NIRVANA is an instrument which provides MCAO (Multi-Conjugate Adaptive Optics) interferometry, combining the light from the two 8.4m telescopes coherently. This configuration offers 23m-baseline optical resolution and the sensitivity of a 12m mirror, with a 2 arcminute diffraction limited field of view.

The integration, alignment and testing of such a big instrument requires a well-organized choreography and AIV planning which has been developed in a hierarchical way. The instrument is divided in largely independent systems, and each consists of various subsystems. Every subsystem integration ends with a verification test and an acceptance procedure. When a certain number of systems are finished and accepted, the instrument AIV phase starts. This hierarchical approach allows testing at early stages with simple setups. The philosophy is to have internally aligned subsystems to be integrated in the instrument optical path, and

extrapolate to finally align the instrument to the telescope.

In this paper we describe the integration of the instrument going through its three basic divisions. Warm optics includes collimator, beam-splitter, derotator, FP-20 camera up to the high-layer AO sensor, plus the alignment of eight star enlargers on each high-layer sensor. Cold optics inside the cryostat is a Cassegrain optical design operating at 60K at wavelengths from 1 to 2.4 microns. Functional testing of the hardware (filter wheel and tip-tilt mirror mainly) and sensitivity at different bands is described. Calibration units are smarts setups for calibration and analysis of the field of view. A fold mirror allows to inject the beams from 24 different fibers strategically placed at different positions.

Results are presented for every step, and a final section outlines the future work to be done until its final commissioning.

9908-113, Session PS2

An instrumental puzzle: the modular integration of AOLI

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AOLI, Adaptive Optics Lucky Imager, is an instrument developed to deliver the highest spatial resolution ever obtained in astrophysics in the visible, ~20 mas, from ground-based telescopes.

This instrument is planned as a double system to use adaptive optics (AO) and lucky imaging (LI), the two most successful techniques to obtain extremely high resolution. LI offers excellent and cheap results on small and medium size telescopes, but it only allows achieving a resolution similar to that of the HST. The addition of low order AO with a new, and really important for the project, geometric wavefront sensor to the system before the LI camera enhances the reachable resolution as it removes the highest scale turbulences maximizing the LI process at larger telescopes.

Aiming at this challenging goal we have built AOLI putting together the expertise of IAC, IoA, UTPC, Univ. Cologne and Univ. La Laguna, each group in charge of a different part of the puzzle. To face the defiance that AOLI represents we have implemented a new philosophy of instrumental prototyping by modularizing all its components: simulator/calibrator, deformable mirror, science and WFS modules. This modular concept, which is really suitable for AOLI, offers huge flexibility regarding the instrument to be developed, the telescope to which this instrument is planned or the addition of future developments and improvements. AOLI has now been restructured not only to make the AIV phase well but also to be able to integrate this system in different ways (f/#, scale, WFS-type,) or to adapt it to different telescopes.

Here we will give the answer to major questions about AOLI's modularity: the why and how of doing it (really well). With such purpose we present a description of the whole instrument, reveal key details of the integration of all its modules and of the verification phase, a crucial step in the development, as well as the preliminary results after its first observing run on the WHT.

9908-114, Session PS2

Accurate high-contrast imaging polarimetry with SPHERE/IRDIS

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We present a comprehensive, numerical model of the instrumental polarization and the polarimetric sensitivity of the SPHERE/IRDIS instrument on the VLT. This model allows us to establish the feasibility of combining Angular Differential Imaging (ADI) with accurately calibrated polarimetry for measuring the degree of linear polarization of directly imaged (sub)stellar companions at near-infrared (NIR) wavelengths. This degree of polarization can be up to ~2% if a companion, such as a gaseous exoplanet or a brown dwarf, is equatorially flattened due to a rapid rotation or if it has patchy clouds in its atmosphere that scatter (and polarize) the thermal radiation that is upwelling from below.

We assess the polarimetric sensitivity of SPHERE/IRDIS by feeding our model real ADI observations of (sub)stellar companions and by applying a range of data-reduction methods and PSF-subtraction algorithms. Combining polarimetry with ADI observations improves the suppression of the (unpolarized) speckle halo, enhancing the contrast by an order of magnitude. We establish the polarimetric accuracy of SPHERE/IRDIS with a Mueller matrix model that describes the complete optical system, thus the telescope and the instrument, and validate this model with internal calibration measurements and observations of unpolarized standard stars. We estimate that after application of the model and associated calibrations, the absolute polarimetric accuracy of SPHERE/IRDIS is a fraction of a percent.

To actually perform combined ADI and polarimetry, pupil-tracking needs to be implemented for IRDIS' polarimetric mode in order to maximize the stability of the quasi-static speckle halo. Whether or not pupil-tracking reduces IRDIS' polarimetric throughput has to be investigated: pupil-tracking limits the range of possible derotator angles, while it is found that at certain angles the derotator induces significant cross-talk.

9908-115, Session PS2

Study of the performance of the SPHERE atmospheric dispersion correctors

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SPHERE was installed at the UT3 Nasmyth focus of the Very Large Telescope in April 2014 and first light occurred on May 4th that year.

Its common path and infrastructure (CPI) features two Atmospheric Dispersion Correctors (ADCs) : a Near Infrared one, and a Visible one. In this paper, we give an overview of the characterisation and performance of these ADC units obtained on sky.

9908-116, Session PS2

The V-SHARK high contrast imager at LBT

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In the framework of the SHARK project the visible channel is a novel instrument synergic to the NIR channel and exploiting the performances of the LBT XAO at visible wavelengths. The status of the project is presented together with the design study of this innovative instrument optimized for high contrast imaging by means of high frame rate. Its expected results will be presented comparing the simulations with the real data of the "4runner" experiment taken at 630nm.

9908-117, Session PS2

The vector vortex coronagraph observing mode on the Subaru SCExAO instrument: current status and performances

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We introduce the Vector Vortex Coronagraph (VVC) observing mode that is part of the Subaru Coronagraphic Extreme AO (SCExAO) instrument, the second-generation near-infrared high-contrast imager of the Subaru Telescope. This focal plane coronagraph mode is now available for use on the SCExAO platform, which is on-track to deliver extreme AO correction for the HiCIAO imager by the 2016A observing period onwards. The SCExAO vortex coronagraph device operates at H-band and can provide better than 100:1 raw starlight rejection at high-Strehl, combined with competitive inner-working angle performances (2 l/D, or 80 mas at H-band) with the Subaru Telescope pupil. Pointing accuracy of better than 1 mas is provided by a dedicated Lyot-based low-order wavefront sensor, combined with AO-generated incoherent "satellite spots" for additional accuracy and photometric calibration. In addition, SCExAO now provides a "speckles nulling" mode available on-sky, using Coherent Differential Imaging (CDI) to beat down the speckle contrast floor. Future improvements currently being considered include the use of a MPIAA lens to remap the telescope pupil to discard the secondary obscuration, effectively improving contrast and inner-working angle (down to 0.9 l/D, the theoretical value for a VVC), as well as the replacement of the HiCIAO imager by an MKIDS array.

We present an overall description of the VVC mode, describe its current and expected near-future performances, and present the most recent on-sky results from the commissioning and early science runs. The VVC coronagraphic mode is straightforward to operate with no extra optics, and is the first H-band vortex to be installed on an 8+m class telescope in the Northern hemisphere.

9908-118, Session PS2

SPHERE IRDIS and IFS astrometric strategy and calibration

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We present the results of the on-sky astrometric characterization of the VLT planet finder SPHERE since the beginning of the instrument operations in May 2014. We first describe the criteria for the selection of the astrometric fields used for calibrating the science data: binaries, multiple systems, and globular clusters. The analysis includes measurements of the pixel scale and the position angle with respect to the north of both detectors of the IRDIS camera and the integral field spectrometer IFS, as well as the on-sky optical distortion of the IRDIS camera. The IRDIS distortion is shown to be dominated by an anamorphism of 0.60+/-0.02% between the horizontal and vertical directions of the detector, i.e. 6 mas at 1 arcsec. The anamorphism is produced by the cylindrical mirrors in the common path structure hence common to all three SPHERE science subsystems (IRDIS, IFS, and ZIMPOL), except for the relative orientation of the detectors. The current estimates of the pixel scale and north angle for IRDIS are 12.25+/-0.01 milliarcseconds/pixel and -1.70+/-0.07 deg. Analyses of the IFS data indicate a pixel scale of 7.46+/-0.01 milliarcseconds/pixel and a north angle of -102.16+/-0.15 deg. Experience on sky showed that the scale is slightly dependent on the environment temperature. Once corrected for this effect, the scale is determined with an error of less than 0.1%. We finally discuss plans for providing astrometric calibration to the SPHERE users outside the instrument consortium.

9908-119, Session PS2

Modeling the transmission and thermal emission in a pupil image behind the Keck II adaptive optics system

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The design and performance of astronomical instruments depend critically on the total system throughput as well as the background emission from the sky and instrumental sources. In designing a pupil stop for background-limited imaging, one seeks to balance throughput and background rejection to optimize measurement signal-to-noise ratios. Many sources affect transmission and emission in infrared imaging behind the Keck Observatory's adaptive optics systems, such as telescope segments, segment gaps, secondary support structure, and AO bench optics. Here we describe an experiment, using the pupil-viewing mode of NIRC2, to image the pupil plane as a function of wavelength. We are developing an empirical model of throughput and background emission as a function of position in the pupil plane. This model will be used in part to inform the optimal design of cold pupils in future instruments, such as the new imaging camera for OSIRIS.

9908-120, Session PS2

GPI observational calibrations XIV: polarimetric contrasts and new data reduction techniques

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The Gemini Planet Imager (GPI) is a recently commissioned instrument installed on the 8-m Gemini South telescope designed for the direct detection and characterization of exoplanets and circumstellar disks. Its optical train consists of an extreme adaptive optics system coupled to a Lyot coronagraph that feeds into an integral field spectrograph. In addition, GPI is equipped with a dual channel polarimetry mode designed to take advantage of the inherently polarized light scattered off circumstellar material, to further suppress the residual seeing halo left uncorrected by the adaptive optics. Here we provide an update on the performance of GPI's polarimetry mode and report on the ongoing development of data reduction techniques. We include an analysis of observations of polarized and unpolarized standard stars, measurements of the polarized twilight sky, as well as observations obtained throughout the GPI Exoplanet Survey (GPIES). In addition, we provide polarimetry contrast curves that demonstrate typical performance throughout the GPIES campaign. We explore how recent advances in data reduction techniques improve upon the achievable contrast in polarimetry mode. In particular, we consider different flux extraction techniques when constructing datacubes from raw data and different methods of subtracting instrumental polarization.

9908-121, Session PS2

Gemini Planet imager observational calibrations XI: pipeline improvements and enhanced calibrations after two years on sky

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The Gemini Planet Imager has been successfully obtaining images and spectra of exoplanets, brown dwarfs, and debris and protoplanetary circumstellar disks, using its combined integral field spectrograph and polarimeter. GPI observations are reconstructed into high-quality astrometrically and photometrically calibrated datacubes using the GPI Data Reduction Pipeline, an open-source software framework continuously developed by our team and available to the community. This paper provides a broad overview of the GPI pipeline, summarizes key lessons learned, and describes improved calibration methods and new capabilities available in the latest release. Enhanced automation better supports observations at the telescope with streamlined and rapid data processing, for instance through real-time assessments of contrast performance and more automated calibration file processing. Several accompanying papers describe in more detail specific aspects of the calibration of GPI data in both spectral and polarimetric modes.

9908-122, Session PS2

Gemini planet imager observational calibration XIII: wavelength calibration improvements with a nonlinear spectral dispersion

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We present improvements to the wavelength calibration for the lenslet-based Integral Field Spectrograph (IFS), that serves as the science instrument for the Gemini Planet Imager (GPI). The GPI IFS features a 2.7" x 2.7" field of view and a 190 x 190 lenslet array (14.1 mas/lenslet) with spectral resolving power ranging from R ? 35 to 78. A unique wavelength solution is determined for each lenslet characterized by a two-dimensional position, an n-dimensional polynomial describing the spectral dispersion, and the rotation of the spectrum with respect to the detector axis. We investigate the non-linearity of the spectral dispersion across all Y, J, H, and K bands through both a comparison to on-sky arc lamp data and simulated instrument performance. Additionally, the 10-hole non-redundant masking mode on GPI provides an alternative measure of wavelength dispersion within a datacube by cross-correlating reference PSFs with science images. This approach can be used to confirm deviations from linear dispersion in the reduced datacubes. We find that the inclusion of a quadratic term provides a factor of 10 improvement in wavelength solution accuracy over the linear solution and is necessary to achieve uncertainties of a few hundredths of a pixel in J band to a few thousands of a pixel in the K bands. This corresponds to a wavelength uncertainty of less than 0.05 nm across all filters. We also investigate the stability of the measured dispersion over time (e.g. correlations with flexure, temperature, seasonal effects).

9908-123, Session PS2

Design of the ERIS calibration unit

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The Enhanced Resolution Imager and Spectrograph (ERIS) is a new-generation instrument for the Cassegrain focus of UT4/VLT telescope, aimed at performing AO-assisted imaging and medium resolution spectroscopy in the 1-5 micron wavelength range. ERIS consists of the 1-5 micron imaging camera NIX, the 1-2.5 micron integral field spectrograph SPIFFIER (a modified version of SPIFFI, currently operating on SINFONI), the AO module and the internal Calibration Unit (ERIS CU).

The purpose of this unit is to provide facilities to calibrate the scientific instruments in the 1-2.5 micron range and to perform troubleshooting and periodic maintenance tests of the AO module (e.g. NGS and LGS WFS internal calibrations and functionalities, ERIS differential flexures) in the 0.5-1 micron range.

The ERIS CU must therefore be designed in order to provide, over the full 0.5-2.5 micron range, the following capabilities: 1) illumination of both the telescope focal plane and the telescope pupil with a high-degree of uniformity; 2) artificial point-like and extended sources onto the telescope focal plane, with high accuracy in both positioning and FWHM; 3) wavelength calibration;4) high stability of these characteristics.

In this poster the design of the ERIS CU, and the solutions adopted to fulfill all these requirements, is described. The CU construction is foreseen to start at the end of 2016.

9908-124, Session PS2

Gemini planet imager observational calibration XII: photometric calibration in the polarimetry mode

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The Gemini Planet Imager (GPI) is a high-contrast instrument specially designed for direct imaging and spectroscopy of exoplanets and debris disks. GPI can also operate as a dual-channel integral field polarimeter. The instrument primarily operates in a coronagraphic mode, enabling high-contrast observations at inner working angles as low as 0.15 arcsec. Traditional coronagraphy poses an obstacle for photometric calibrations since the majority of on-axis starlight is blocked. To enable accurate photometry relative to the occulted central star, a diffractive grid in a pupil plane is used to create a set of faint copies, named satellite spots, of the occulted star at specified locations and relative intensities in the field of view. We describe the method we developed to perform the photometric calibration of coronagraphic observations in polarimetry mode using these fiducial satellite spots. Although this calibration method is based on the same principle as what is currently being used in spectroscopy mode, a separate set of data processing procedures is needed for performing the photometric calibration on broadband polarimetric images instead of spectral cubes. In polarimetry mode, the satellite spots are not diffraction-limited PSFs but are smeared out into long oval shapes due to their chromaticity. We characterize the uncertainty associated with this calibration method and describe the implementation of these techniques into the GPI Data Reduction Pipeline. Alternatively, the photometric calibration can be performed by scaling the photometry in polarimetry mode to the photometrically calibrated response in spectroscopy mode. We explore this scaling factor by characterizing the flux ratio of satellite spots between the polarimetry and spectroscopy observing modes.

9908-125, Session PS2

An ADC for the SAM on the SOAR Telescope

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SAM (Soar Adaptive-optics Module), the SOAR (Southern Observatory for Astrophysical Research) GLAO facility is in service since 2009, first with NGS (Natural Guide Star) and since 2011, with a UV, 355nm, LGS (Laser Guide Star).

The atmospheric WF error is therefore measured at 355nm and the star images are corrected in the visible range (BVRI bands). An ADC is required for High Resolution imaging at low telescope elevation, especially in the shorter Wavelengths range of the visible spectrum.

The ADC is based on 80mm diameter rotating prisms, it is a compact unit, fully automated, can be inserted or removed from the tightly constrained SAM collimated beam space-envelope, adjusts to the Parallactic angle and corrects the Atmospheric Dispersion magnitude.

Here we present the optical and opto-mechanical design, the control design, the operational strategy and performance results obtained from extensive use in on-sky HR Speckle Imaging.

9908-126, Session PS2

Infrared photometry with 'wall-eyed' pointing at the Large Binocular Telescope

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Ground-based observations in the thermal infrared are complicated by the brightness and temporal variability of the night sky at these wavelengths, as well as the dearth of wide-field detectors sensitive to >2 microns. Small-field detectors have traditionally forced observers to slew telescopes back-and-forth between science and comparison targets to perform precision photometry, except in the rare event that both targets are just a few arcseconds apart. This leads to a loss of observing efficiency, and the possible introduction of instrumental systematics. Here we present a new pointing mode of the Large Binocular Telescope to circumvent these issues. The Large Binocular Telescope, located in southern Arizona, has two 8.4-m primary mirrors which can be aimed separately at science and comparison targets, with acceptable separations of as much as ~2 arcminutes. Both light paths receive separate AO corrections, and the Large Binocular Telescope Interferometer instrument can perform simultaneous direct imaging with both telescope sides, with either a 3-5 micron or 7-25 micron detector. We applied this 'wall-eyed' pointing mode to an observation of an exoplanet transiting in front of its host star at 3.3 microns, deep in the atmospheric bog of the thermal infrared. We used a 10x10 arcsecond detector, and yet could use a comparison star 31.2 asecs away from the transiting system. We will present constrains on the photometric precision we found, and elaborate on possible improvements and science avenues this would level of precision would open up.

9908-127, Session PS2

SPHERE on-sky performance compared with budget predictions

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The SPHERE (spectro-photometric exoplanet research) extreme-AO planet hunter saw first light at the VLT observatory on Mount Paranal in May 2004 after ten years of development. Great efforts were put into modelling its performance, particularly in terms of achievable contrast, and to budgeting instrumental features such as wavefront errors, optical transmission, dust contamination, surface cosmetics, etc. In this paper we aim at comparing predicted performance with measured performance at each of the instrument's three focal planes, the near infrared dual imaging camera IRDIS, the near infrared integral field spectrograph IFS and the visible polarimetric camera ZIMPOL. In addition to comparing on-sky contrast curves and calibrated transmission measurements obtained for each camera, we also compare the PSD-based wavefront error budget with the PSD calculated from in-situ wavefront maps obtained thanks to a Zernike phase mask, ZELDA, implemented in the infrared coronagraph wheel.

One of the most critical elements of the SPHERE system is its high-order deformable mirror, a prototype 40x40 actuator piezo stack design developed in parallel with the instrument development. The development was a success, as witnessed by the instrument performance, in spite of some bad surprises discovered on the way. The devastating effects of operating without taking properly into account the loss of several actuators and the thermally and temporally induced variations in the HODM shape will be analyzed, and the actions taken to mitigate these defects through the introduction of specially designed Lyot stops and activation of one of the mirrors in the optical train will be described.

9908-128, Session PS2

Near-infrared adaptive optics imaging and spectro-polarimetry with the infrared camera and spectrograph of the Subaru Telescope

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We have developed the near-infrared high-spatial resolution imaging and spectro-polarimetric modes with the laser guide adaptive optics system (AO188) and the Infrared Camera and Spectrograph (IRCS) of the 8.2-m Subaru telescope. A LiNbO3 Wollaston prism (as dual beam analyzer) and focal plane masks were installed into the camera section of the IRCS cryostat, enabling us to perform the low- and medium resolution grism spectro-polarimetry (R = 100-1960) as well as the imaging polarimetry, in conjunction with a half-wave retarder, which had been introduced for the HiCIAO instrument primarily, at the front of the AO188 system. The designed wavelength coverage of the Wollaston prism is 0.8-5 micron, although the present coverage of polarimetry is 0.95-2.5 micron due to limitations on the retarder and the dichroic beam splitter of AO188. The focal plane masks, which are reflecting mirror or slits made with tungsten carbide, provide two or four rectangular focal plane apertures with an individual field of view of 4.4 arcsec x 21 arcsec or 4.4 x 54 arcsec for the imaging polarimetry, or two or four slits with a width of 0.10, 0.15, 0.225, and 0.60 arcsec and a length of 4.4 arcsec for the spectropolarimetry. The Wollaston prism and polarimetry masks were installed on June and July 2013, and the polarimetric modes had the first light on October 2013. The polarization efficiency is 88-96% and 55-80% at maximum for the imaging- and spectro-polarimetry, respectively, and it depends heavily on the angle of image rotator of AO188. The measured instrumental polarization, which is introduced by the telescope tertiary mirror mainly, is 0.3-0.7%. We describe the design and current performance of the polarimetric function.

9908-129, Session PS2

NIX, the imager for ERIS: the AO instrument for the VLT

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ERIS will be the next generation AO facility on the VLT, combining the heritage of NACO imaging with the spectroscopic capabilities of an upgraded SPIFFI. Here we report on the all-new NIX imager that will deliver diffraction-limited imaging from the J to Mp band. The instrument will be equipped with both apodizing phase plates and sparse aperture masks to provide high-angular resolution imagery, especially suited for exoplanet imaging and characterisation. This paper will detail the

instrument's design and how it is expected to address a broad range of science cases, from detailed investigations of the galactic centre at the highest resolutions, to studying stellar populations and the evolution of more distant galaxies.

9908-130, Session PS2

Pushing down with the contrast: scientific performances with SPHERE-IFS

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The VLT second generation instrument SPHERE was commissioned in the Summer of 2014, and offered to the community in the Spring of 2015. SPHERE is a high contrast imager that exploits its three scientific channels in order to observe and discover young warm exoplanets in the glare of their host stars. The three scientific instrument are: ZIMPOL, a polarization analyzer and imager that works in the visible range of wavelength, IRDIS a dual band imager and spectro polarimetric Camera that works in the NIR range up to K band, and IFS, an integral field spectrograph working in the YJH band.Very important is the complementarity between IRDIS and IFS. The former has a larger Field of view (about 12 arcseconds) while the IFS push its examination very close to the central star (FoV ~ 1.7 arcsec). In one year of operational time a lot of very interesting scientific cases were investigated and very nice results were gathered. In this paper we would like to focus the attention on the high quality results and performances obtained with the IFS

9908-131, Session PS3

H2RG detector characterization for RIMAS and instrument efficiencies

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The Rapid infrared IMAger-Spectrometer (RIMAS) is a near-infrared (NIR) imager and spectrometer that will quickly follow-up gamma-ray burst afterglows on the 4.3-meter Discovery Channel Telescope (DCT). RIMAS has two optical arms which allows simultaneous coverage over two bandpasses (YJ and HK) in either imaging or spectroscopy mode. RIMAS utilizes two Teledyne HgCdTe HXRG detectors controlled by Astronomical Research Cameras, Inc. (ARC/Leach) drivers. We report the laboratory characterization of RIMAS's detectors: read noise, linearity, dark current, conversion gain, and quantum efficiency. We also present RIMAS's instrument efficiency from atmospheric transmission models and optics data (both telescope and instrument).

9908-132, Session PS3

Optical design for wide-field imaging and multi-object spectrograph for Antarctic Infrared Telescope (AIR-C)

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The design of the wide-field infrared camera for Antarctic 2.5m Infrared telescope, which is planned to construct at Dome F, is presented. The camera was designed with off-axis optics and achieved the image quality of refraction limited for 2.5m telescope at 1-5 micron meters. The array sensors with two 2K by 2K InSb and one 2K by 2K HgCdTe will be equipped, which allow the simultaneous three-band observations. The field of view is 7.5'x7.5' with 0.21"/pixel. To enjoy the stable atmosphere with extremely low perceptible water vapor and the cadence of the polar winter, the camera will be dedicated to the transit observations of exoplanets. The function of a multi-object spectroscopic mode with low spectra resolution (r~50-100) will be added for the spectroscopic transit observation at 1-5 micron. The capability will be very useful for the study of water vapor in the atmosphere of, e.g., super earths.

9908-134, Session PS3

DOTIFS: spectrograph optical and opto-mechanical design

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In this work, we present spectrograph optical and opto-mechanical design of the Devasthal Optical Telescope Integral Field Spectrograph (DOTIFS), which is a new multi-Integral Field Unit (multi-IFU) Spectrograph to the new 3.6m Devasthal Optical Telescope. DOTIFS is being fabricated by Inter University Center for Astronomy and Astrophysics instrumentation group in Pune, India.

Light coming from multiple extended sources are gathered by 16 deployable IFUs and transferred to 8 indentical spectrographs via optical fibers. Each IFU has 8.7" x 7.4" field of view with 144 (12 x 12) spaxel elements with 0.8" hexagonal shape sampling. Lights coming from IFUs are dispersed by eight identical single channel spectrographs. With a single exposure, spectra of 2,304 spatial elements from entire 370nm - 740nm wavelength range is obtained with R~1800.

DOTIFS spectrograph is comprised of fiber slit, f=520mm collimator, broadband filter, dispersion element, f=195mm camera and 4K by 2K CCD in order. The 8cm fiber slit is comprised of 288 fibers coming from two IFUs. The F/4 collimator is comprised of 3 singlets and 2 doublets, and the fast F/1.5 camera is comprised of 3 singlets and 3 doublets. Collimator and camera optics are designed base on South African Large Telescope Robert Stobie Spectrograph, which has similar optical properties. The design is fully re-optimized to fulfill requirements of DOTIFS. Every surfaces are spherical to make ease of fabrication and alignment process. To maintain good transmission down to 370nm, calcium fluoride and high transmission optical glasses have been used. Pupil size is determined as 130mm from spectral resolution and budget requirements. Volume Phase Holographic grating is selected as a dispersion element to maximize the grating efficiency and to minimize the size of the optics. The blazed wavelength of the VPH grating is shifted to blueward from the center to minimize contamination by Littrow ghost. Wide band filter is used to sort out light other than working wavelength range. Filter is tilted by 10 degrees to effectively eliminate ghost reflection coming from the camera optics. E2V 4K by 2K CCD is used and graded coated to maximize quantum efficiency. Fiber slit is oriented along 2K direction and the light is dispersed along the 4K direction although only 3K pixels will be used. On CCD, image height of each spectra is 2.5 pixel and the center to center separation between fiber spectrums is determined as ~7 pixels.

Spectrograph opto-mechanics are designed to accommodate spectrograph optics in gravity-variant environment. Spectrographs will be located around main Cassegrain port instrument of the telescope and oriented in various direction with respect to the gravity.

We will assemble two spectrographs first and extend it to eight in total in future. The design is finalized, and the components are ordered and being fabricated by manufacturers. We expect to begin assembly in the middle of 2016.

9908-135, Session PS3

GravityCam: wide-field, high-resolution imaging and high-speed photometry instrument

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GravityCam is a new instrumental concept designed to provide simultaneously wide field imaging (>30 arcmin) with high-resolution (~0.15 arcsec) and high time resolution photometry (~40 msec) on 2-5m class ground-based telescopes.

The science case for GravityCam is very strong indeed. It can provide unique datasets for studies of exoplanets, asteroseismology, Kuiper belt and Oort Cloud populations and dark matter surveys in distant clusters of galaxies by weak gravitational shear studies.

GravityCam will increase dramatically the number of detectable planets down to masses less than that of the Earth. At present known exoplanet detection is easiest with large Jupiter mass objects orbiting close to the central star. It is widely believed that the population of exoplanets is much greater at lower masses where detection is extremely difficult. Microlensing occurs when one star passes in front of another, greatly increasing the brightness of the more distant object. The symmetry of the light curve may be broken by the presence of a planet in orbit ground the lensing star. Even very small objects, down to perhaps the mass of the moon can be detected. GravityCam will look at 6 relatively unobscured fields such as Baade's window, close to the centre of our galaxy, each extending over a field of about 30 arcminute square. An array of electron multiplying CCDs operating in Lucky Imaging mode will record photometric data on approximately 20 million stars night after night. On telescopes such as the NTT 3.6 m telescope we predict a few new microlensing events will be detected each night and that planetary detections should occur perhaps once per week. Such a survey would give for the first time a reliable planetary mass function.

GravityCam will also for the first time give extensive statistics on the short medium and long-term variability of a large population of stars, providing a unique data set for asteroseismology and variable star studies.

The high time resolution of GravityCam will allow access to the small end of the Kuiper belt size distribution and potentially the Oort cloud by studying serendipitious occultations of stars by small solar system bodies. These occultations can reveal atmospheres, satellites and rings around these occulting objects.

By observing the fields of rich clusters of galaxies, GravityCam also has the capacity to greatly improve the quality and sensitivity of weak shear studies that are critical to understanding the nature and distribution of dark matter in the universe. Such studies are usually limited by the relatively poor angular resolution possible on even the best ground-based observatories.

9908-136, Session PS3

Advances in the development of a Mach-Zehnder interferometric Doppler imager for seismology of giant planets

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Seismology of giant planets allows the study of internal structure, as helioseismology did for the Sun. With the detection of acoustic oscillations on Jupiter (Gaulme et al, 2011) and surface modes on Saturn (Hedman and Nicholson, 2013), a new window on the interior of giant planet is now open.

The best way to measure the frequencies of global modes consists in recording periodic variations of the Doppler shifts of solar lines reflected at the surface of planets. Sounding different depths into the planet requires a sufficient spatial resolution to distinguish the different mode degrees and a long enough time series to get a good precision on the frequency measurements. The JOVIAL project, in collaboration with France, USA, and Japan, foresees the installation of three instruments around the Earth for almost continuous observations during several weeks.

The instrument is an imaging Fourier tachometer. It is based on a Mach-Zehnder interferometer with fixed optical path difference that maximizes the sensitivity. At any point on the surface of the planet, the projected velocity on the line of sight induced a linear shift in the phase of the fringe pattern. The Mach-Zehnder interferometer provides four output images with interferometric fringes separated by a phase of pi/2. A combination of the four outputs, based on the ABCD algorithm (Shao et al,1988) permits the reconstruction of the phase map, therefore of the velocity field at the surface of the planet. The precise calibration of the four outputs is made possible by a modulation of the optical path difference. The thermal stability of the optical path difference is a crucial condition of the measurements. The choice of the optical components and the design of the interferometer were chosen to minimize the thermal sensitivity.

A first prototype of the instrument was built at Observatoire de la Côte d'Azur and tested at the laboratory and on the sky. Atmospheric turbulence and guiding errors affects the measurements. A fast tip-tilt mirror was used to limit the degradation. The bias due to remaining motions was estimated and a correction can be applied. A large-field Adaptive Optics correction will be applied for future observations.

The achieved performance in term of sensitivity and stability are close to theoretical values and will allow detection of modes with amplitudes as low as 5 cm/s on Jupiter after two weeks of observations, in the frame of the JOVIAL network. A precision of a few m/s in wind measurements is expected. The instrument was studied and designed in view of a future space mission. The present results demonstrate the technical readiness of the concept for missions for Saturn or for the ice giant planets.

9908-137, Session PS3

Cryogenic transmissive optics for the rapid infrared imager/spectrometer

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The Rapid infrared IMAger-Spectrometer (RIMAS) is a near infrared (NIR) instrument designed for operation on Lowell Observatory's 4.3 meter Discovery Channel Telescope (DCT) located in Happy Jack, Arizona. Once commissioned, RIMAS will complement the Swift space observatory by quickly responding to transient astronomical sources. Due to space and weight limitations on the telescope's "instrument cube", the instrument design is fully refractive to make it as compact as possible. The optics include a collimator, a dichroic beamsplitter, two cameras and a set of filters and gratings for each of the two optical paths. Wavelengths from 0.97-1.33 microns are reflected by the dichroic and 1.48-2.39 microns are transmitted. RIMAS is cooled to cryogenic temperatures (~60 K) to reduce thermal radiation at the longest wavelengths of this spectral range. A thermal compensator design has been implemented to assist alignment at room temperature. The performance of the aligned and cooled optical system is presented.

9908-138, Session PS3

Design, assembly, and performance of the low-resolution spectrograph 2 integral field unit

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The Low Resolution Spectrograph 2 (LRS2) was recently deployed on the Hobby-Eberly Telescope (HET). LRS2 consists of four spectrographic channels, each covering adjacent wavelength bands from 360-1050nm which are fed with a fiber optic integral field unit (IFU). The integral field unit developed for this instrument represents a transformative approach to expanding the wavelength coverage of integral field spectrographs. The unique input feed of the IFU serves two functions; combining the wavelength coverage of two spectrographic channels to one spatial field on sky, and expanding the field of view of each individual fiber to eliminate the interstitial space between fibers on sky. The spectral multiplexing is achieved with dichroic beam splitter and collimator, while the focal reduction is achieved with a pair of micro lens arrays. The optical components required micron scale alignment precision in a compact mechanical package to allow integration on the telescope focal surface. Here we report on the design, assembly, and performance of the IFU.

9908-139, Session PS3

Development of a prototype of the Tomo-e Gozen wide-field CMOS camera

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The Tomo-e Gozen is an extremely wide-field optical camera optimized for time-domain surveys by the Kiso 105-cm Schmidt telescope of the University of Tokyo. It is capable of taking time-series frames with sub-second resolution and a field of view of 20 square degrees achieved by 84 chips of front-illuminated 2k x 1k CMOS sensors with microlensed 19 microns pixels. The sensitive wavelength range is approximately 400 nm to 650 nm. The sensors are placed on the spherical focal plane of the telescope with a curvature radius of 3,300 mm and operated at room temperature without mechanical coolers owing to low dark current. Optical filters are exchanged manually in daytime. The simple design, not using a cryostat and moving parts, enables us to make a light-weight camera system with good maintainability. The time-domain surveys by the Tomo-e Gozen will produce an enormous amount of movie data unlike ever experienced before. The data production rate reaches 30 TByte/night in continuous full-frame acquisitions at 2 Hz. Faint and transient events are searched from the movie big-data by using a real-time processing system with technologies on movie recognition and machine learning.

We have developed a prototype model of the Tomo-e Gozen (Tomo-e PM) with eight sensor chips arranged in a line along the RA direction to evaluate the basic design for the Tomo-e Gozen. The field of view of each chip is 39.7 arcmin in RA x 22.4 arcmin in DEC. The spatial gaps between adjacent chips are 25 arcmin. The maximum frame rate is 2 frames/sec in full-frame read out. The sensor chips are fixed on a flat base-plate via column blocks, the tops of which are diagonally cut precisely, to place them parallel to the spherical focal plane. The base plate with sensors is housed in a light-weight chassis with eight transparent windows of 50 mm x 50 mm, which can be exchanged to optical filters independently. The total weight of the camera body is approximately 30 kg. Video data from

the eight sensor chips is processed by eight pieces of 16-channel 16-bit 500 kHz AD converter boards and then transferred to I/O boards on two control PCs via LVDS serializer/deserializer boards. The read out noise and full-well are 7 e- / 55,000 e-, 4 e- / 23,000 e-, and 2 e- / 6,100 e- in low-, mid-, and high-gain modes, respectively. Estimated 10-sigma limiting magnitudes with no-filter are 16.0, 17.6, 18.8, and 20.2 mag at 0.1, 1, 10, and 100 sec integration times, respectively. Commissioning runs for Tomo-e PM have been successfully performed in the end of 2015. Fast-moving objects such as faint meteors, satellites, and asteroids have been observed for checking performance of Tomo-e PM in high frame rate observations.

9908-140, Session PS3

The Wide Integral Field Infrared Spectrograph (WIFIS): optomechanical design and development

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We present the optomechanical design and development of the Wide Integral Field Infrared Spectrograph (WIFIS). When commissioned on the 2.3 m Bok Telescope, WIFIS will provide an unrivaled integral field size of 20” ? 50” for an infrared integral-field spectrograph at the spectral resolving power R = 2000?3000. Its spectral range covers the zJ- and most of the H-band (0.9–1.7 ?m) with a focus on the former. The main optics of WIFIS consists of a set of re-imaging off-axis parabolic mirrors and an image slicer-based integral field unit, which are followed by a collimator system, a reflective grating as a disperser, and a spectrograph camera composed of six lenses. The re-imaging optics is readily replaceable to fit a different telescope beam, and this makes WIFIS a highly versatile instrument that can be easily used at a different telescope. Its grating shift mechanism allows for two selective reflective angles from the same grating for the zJ- and H-band, respectively. The majority of the WIFIS optical components are mounted inside an aluminum optical bench at a room temperature. A cryogenic dewar operating at liquid nitrogen temperature contains a field lens of the spectrograph camera, a filter wheel, an Hawaii-2RG 1.7 ?m-cutoff detector array and its focusing stage, and readout electronics. There are two optical subsystems for WIFIS: the calibration unit and the guide camera system. The calibration unit consists of an integrating sphere for flat fielding, a thorium-argon lamp for wavelength calibration, and an optical system to simulate the telescope beam. The guider camera system provides an auxiliary photometric capability of griz- and H?-band for a 5? ? 5? off-axis field in addition to the basic guiding capability.

By virtue of its large integral-field size, WIFIS will be a highly competitive instrument for seeing-limited astronomical investigations of the dynamics and chemistry of extended objects in the near-infrared wavebands. Targets for the WIFIS first-light sciences include young supernova remnants and star-forming regions in the Galaxy, stellar populations in nearby elliptical and spiral bulges, massive star formation in nearby spiral galaxies, and galaxy mergers at moderate redshifts. We plan to commission WIFIS on the Bok Telescope in early 2016.

9908-141, Session PS3

Suspended particulate matter effects on daytime star sensor design and performance

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Within the last few years, efforts to find a more reliable replacement for Global Positioning System has increased. Various reasons for trying to compensate GPS exist. From its vulnerability to jamming and spoofing in severe conditions to its unavailability in interplanetary missions such as NASA’s 2030 Mars exploration. This challenge is even more critical for developing countries not owning national satellite navigation system. Usually poor legitimate alternative coverage of regional satellite positioning systems such as GLONASS, IRNSS or BeiDou is also provided for such countries. One of the strong candidates for recruiting this comprehensive navigation system is believed to be celestial navigation. In order to utilize star sensors as a mean of celestial navigation in lieu of GPS, important modifications such as altering the performing wavelength from visible light of night sky to infrared imaging of daytime stars is obligatory. Electronic imaging devices such as Infrared Focal Plane Array (IRFPA) for capturing shortwave infrared wavelength (SWIR) are available for applications such as night vision or target search and tracking. However extension of their application to ground based astronomy imaging in place of massive telescopes is yet to be investigated. Especially in lower altitudes that atmosphere effects are bold and influential. Atmospheric layers absorb, scatter and diffract star lights in J, H and K bands of SWIR more as the altitude is decreased. The Effect of natural phenomenon of elements consisting atmosphere such as atmospheric opacity due to excessive Carbone Dioxide accumulation in central cities and water vapor close to oceans and lakes are considerable. But the main concern rests with the undesirable effect of atmospheric suspended Particulate Matter (PM) from dessert dust augmenting these days. These particles vary in size below 2.5 ?m and intensify Mie and Non-selective scattering effect since PMs are either the same size as K band of infrared wavelength or larger. In this paper component design of infrared camera for ground based position determination is considered. Infrared detectors such as InGaAs are suitable choices available off the shelf. The contrast between selection of infrared bands and environmental condition requires accurate consideration therefore decision making between operating wavelength, magnitude, field of view, exposure time, signal to noise ratio, quantum efficiency, full well capacity etc. for different altitudes from on the ground up to typical surveillance flight height is analyzed. Using MODTRAN software for aerosol analysis, optical properties of infrared camera are determined with various PM intensity. Potential regions of interest are extracted according to forecast site reports and the minimum appropriate altitude for holding an infrared star sensor to air is determined. While dry regions suffers from semi-unnatural atmospheric phenomenon which confines the performance, the analysis can improve the insight on celestial navigation future for precise position determination globally.

9908-142, Session PS3

Optical design of a multi-resolution, single-shot spectrograph

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Multi-object or integral field spectrographs today are recognized techniques for achieving simultaneous spectroscopic observations of different or extended sky objects with a high multiplex factor. In this communication is described a complementary approach for realizing similar measurements under different spectral resolutions at the same time. Herein is explained the basic principle of this new type of spectrometer, that is based on the utilization of an optical pupil slicer. An optical design inspired from an already studied instrument is then presented and commented for the sake of illustration. Technical issues about the pupil slicer and diffractive components are also discussed. We finally conclude on the potential advantages and drawbacks of the proposed system.

9908-143, Session PS3

Survey of materials and coatings suitable for controlling stray light from the near-UV to the near-IR

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Controlling stray light through the use of black surfaces is common practice in the design of astronomical instruments and telescopes. While the geometry of the elements that make up the stray light design – baffles, enclosures, masks, etc. – is key, so too are the materials and coatings used to make them. We present a survey of reflective spectra from 300nm to 2500nm of a range of materials used for stray light control, as well as other materials commonly found in instrumentation and telescopes.

9908-144, Session PS3

NIR camera and spectrograph SWIMS for TAO 6.5m telescope: overview and development status

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Simultaneous-color Wide-field Infrared Multi-object Spectrograph, SWIMS, is one of the first generation instruments for University of Tokyo Atacama Observatory 6.5m Telescope now being constructed at the summit of Co. Chajnantor in northern Chile. Thanks to the high altitude (5640m altitude) and dry climate (precipitable water vapor~0.5mm) of the site, almost continuous atmospheric window from 0.9 to 2.5 um appears.

SWIMS has a field of view of 9.6 arcmin in diameter, and a dichroic mirror is inserted in the collimated beam to split it into two arms, one covering 0.9-1.45 micron and the other 1.45-2.5 micron. It is capable of two-color simultaneous imaging or R~1000 multi-object spectroscopy at 0.9-2.5 micron wavelength range with a single exposure, and enables us to carry out efficient NIR imaging/spectroscopic surveys.

Focal plane of each arm is planned to be covered by four HAWAII-2RGs focal-plane arrays, however, currently only two arrays are procured which provide FoV of 8.6 x 4.3 square arcminutes, with a pixel scale of 0.126arcmin.

The telescope focal plane is covered by a separate dewar for a multi-object slit mask exchange unit (MOSU), which has a carousel to store multi-object slits (MOS) masks and gate valve to separate the main dewar from the MOSU dewar.

MOS masks cover 5 x 8.6 arcmin, and maximum ~30 slits with length of 15 arcsec can be arranged on it. The masks are installed in a rotating carousel in the MOSU dewar which can store maximum 20 of them, and a robotic hand place them at the focal plane or house into the carousel. An IFU module covering 17 x 13 arcsec with 26 slitlets of 0.5arcsec width are also being developed. It is designed to be compact enough that it can be stored in the MOSU carousel and can be handled by the robotic hand as well.

The main cryostat dewar has a cylindrical shape 1.5m in height and 1.3m in diameter, and cooled down below 100K by a single GM-cycle cooler. Cool down time is almost one week with assistance of liquefied nitrogen, and temperatures reach <100K at optical components and <80K at detectors. The MOSU has an additional GM-cycle cooler whose cool down time is less than 2 days without any assist.

The cryostats are contained in a box of 2m x 2m x 2m, and its total weight is approximately 2.5ton. The whole instrument is installed on the Nasmyth focus of the TAO 6.5m telescope with an instrument rotator.

SWIMS is expected to be transported to the Subaru telescope in 2016 and planned to be install on the Cassegrain focus of the telescope to carry out first-light and engineering observations. After the completion of the 6.5m telescope, its collimator lens system will be exchanged to that for the 6.5m telescope, as the optical parameters are different, and will be sent to Chile and see the scientific first light in FY 2018.

9908-145, Session PS3

Developing scanning-slit spectrograph for imaging the Sun

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Spectral imaging is one of the important ways to directly obtain the images of the solar atmosphere at different heights. Computing doppler shift for each spatial position gives the line of sight velocity maps. For chosen spectral line, as each part of it forms at different heights in solar atmosphere, obtaining spectral information near simultaneously at all spatial locations can give a rough idea about three dimensional view. The instrument is a back-end for a telescope with tracking system i.e. stable image of the sun is projected onto the focal plane at all times. The instrument consists of three modules – image stabilization system, scanning-slit assembly and spectrograph assembly. Image stabilization system is a closed loop control system to maintain the finer stability of the image. Scanning-slit assembly is a module that can linearly move in one direction to sweep the region of interest in the image. Spectrograph assembly consists of another slit, optics and dispersing element along with the detector so that spectral information about spatial locations on the slit can be obtained. This module is designed to obtain Intensity vs. (y,?) (y – along the slit) and as the scanning-slit is swept along the x-direction, Intensity vs. (x,y,?) information is built. The spatial resolution will be seeing limited as there's no correction system. Field of view is 3 arc minute along the slit direction, as the features of interest include sunspots and surrounding region. For testing, a front end system of 140mm clear aperture with f/16 is being used. The dispersing element is a reflecting grating with 1200 grooves/mm. For 656.3 nm (H-alpha line) spectral resolution is 3.5 pm in second order. Linear dispersion is about 3.8 pm/pixel for pixel size of 7.5 um, indicating that slit-width limited spectral resolution can be obtained. Image stabilization system is aimed to achieve a stability of 1.5 arcsec using image correlation maximization technique. It is also aimed to complete one set of observations (120 frames) in 300 seconds.

9908-146, Session PS3

Development status of the mid-infrared two-field camera and spectrograph MIMIZUKU for the TAO 6.5-m Telescope

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MIMIZUKU is the first-generation mid-infrared instrument for the University of Tokyo Atacama Observatory (TAO) 6.5-m telescope. The site is the summit of Co. Chajnantor in northern Chile. Thanks to its high altitude (5640 m) and dry climate, good atmospheric windows are available from near-infrared to 38-micron region. To utilize this uniqueness, MIMIZUKU covers the 2 - 38 micron region with three channels (NIR, MIRS, and MIRL). NIR covers the 2 - 5.3 micron region with a HAWAII-1RG array. MIRS covers the 6.8 - 26 micron region with an AQUARIUS array. And MIRL covers the 24 - 38 micron region with a Si:Sb array developed by DRS. The field of view is 1.2', 2.0', and 31'' on a side for the NIR, MIRS, and MIRL, respectively. Each channel also has a capability of low-resolution spectroscopy (R = 64 - 620). In addition, MIMIZUKU is capable of observing two separate fields (distance < 25') simultaneously by using a unique mechanism called "Field Stacker". By allocating the fields to target and calibrator, time-variable atmospheric transmittance can be calibrated accurately. This capability improves photometric and spectroscopic accuracy, and difficult observations like long-term monitoring and spectroscopy in low-transmittance bands will be realized even in ground-based mid-infrared observations.

The development of MIMIZUKU is in the final phase, and the cryogenic system and cryogenic optics have got ready. The development of the Field Stacker and detector controlling system are given by Uchiyama et al. and Okada et al., respectively. In this presentation, the overview, current development results (especially for the cryogenic system and optics), and future prospects of MIMIZUKU will be reported.

As for the cryogenic system, its goal is to cool the optics and detectors down to sufficiently low temperature for suppressing instrumental background and detector dark current. The temperature required for the optics is 27 K, and that for the detector is 5, 7, and 37 K for the NIR, MIRS, and MIRL, respectively. These temperatures had not been achieved previously because of insufficient thermal conductivity of thermal paths. After improving contact thermal conductance and refurbishing the paths with oxygen-free high-conductivity copper, the required temperatures got achieved even with adding detector thermal dissipation.

As for the optics, its re-fabrication and re-assembly are successfully finished. The optics consists of gold-plated aluminum mirrors to maximize throughput and to match thermal expansion coefficient with the aluminum optical bench. However, the combination of gold and aluminum is weak against galvanic corrosion, and our mirrors have been degraded once. After the fabrication and assembly, the imaging performance of the optics is checked by optical imaging test, and enough capability to achieve diffraction-limited mid-infrared image and seeing-limited near-infrared image is confirmed.

The development works are to be completed in FY 2015. After that, MIMIZUKU will be transferred to the Subaru telescope for its commissioning, and initial science operation is planned in FY 2017 - 2018. After the completion of TAO 6.5-m telescope, MIMIZUKU will be delivered to the TAO, and the first light at the TAO will be around FY 2019.

9908-147, Session PS3

Conceptual design of wide-field focal plane with InGaAs image sensors

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The success of Sloan Digital Sky Survey (SDSS) had forced us to recognize the importance of wide-field survey and many imaging survey projects, such as Dark Energy Survey, Hyper Suprime-Cam (HSC), LSST, have been started to probe the universe much deeper than SDSS. On the other hand, ground-based wide-field survey project in infrared wavelength with comparable width and depth to the optical surveys seems to be inactive and, instead, it looks that the effort is concentrated on space mission such as Euclid and WFIRST.

Recently, an application of InGaAs image sensor which is sensitive to the infrared wavelength (1-1.7um) for astronomy has been considered seriously (Nakaya et al. in this conference). The merit to adopt this sensor is the availability with reasonable cost (compared to the other infrared sensors) since the sensor is designed for industrial use. Nakaya et al. intensively tested InGaAs image sensor of 128 x 128 pixel format with 20 um pixel pitch developed by Hamamatsu Photonics K. K., although it is not the largest format provided by Hamamatsu (640 x 512 format). They found that the InGaAs image sensors have promising performance (e.g. linearity, wavelength response, intra-pixel response) except for the readout noise and dark current. Such shortcomings are suggested to be improved by replacing the CMOS readout IC. Therefore, once the technique to enlarge the sensor format is developed, the InGaAs image sensors could be used for astronomy and open a new window for the wide-field infrared imaging survey.

We consider the possibility to employ this sensor for astronomical instrument based on our experience accumulated during the development of HSC (Miyazaki et al. 2012; Komiyama et al. 2010). On the focal plane of HSC, 116 2k4k CCDs are tiled with minimum gaps (0.3mm) between CCDs together with a focal plane flatness of +/-17um, attaining 90% filling factor of focal plane). Our experience is of great help to realize the wide-field camera of InGaAs sensors with higher survey capability. In the present paper, we summarize the technical difficulties for developing camera with many InGaAs sensors and show the appropriate solutions for the difficulties.

The most difficult part would be the development of focal plane assembly. We show the basic idea how to mount the sensors, feed the cable for the front-end electronics, and form as a dewar. The chip size considered here is 22 x 22 mm, which comes from the maximum size of the CMOS readout IC. The design should be scalable so that the number of sensors can be maximized to realize the field of view as wide as possible.

The other difficulty is that the required operating temperature of InGaAs image sensor is -130 deg which is 30 deg lower than operating temperature of CCDs (-100 deg). We carried out the thermal calculation and estimate the power required to cooling down the sensor adequately. We also show an idea to reduce the dominant thermal inflow by radiation from the entrance window.

9908-148, Session PS3

The SKA low frequency aperture array: from design to verification systems

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The deployment of the Square Kilometre Array (SKA) starts with a ~10% instrument, phase 1, commencing with construction in 2018. This includes the SKA1-LOW, a sparse Aperture Array (AA) covering 50 to at least 350MHz. SKA1-LOW will consist of 512 stations, each with 256 antennas creating a total of more than 130.000 antennas. The configuration will be very closed packed with 90-95% of the antennas within a 3km radius inner area and the remaining collecting area situated on three spiral arms, extending to a radius of ~45km.

The Aperture Array Design and Construction (AADC) Consortium is responsible for the design of the stations, the signal transport to a processing facility and the station beamforming, including the local software. The design of this system poses a number of challenges, not only in terms of performance but also due to the sheer volume of the parts (antennas, receivers etc.) and the output data rate. In order to mitigate the design risks, verification systems have and will be realized. Initially small 16 antenna systems have been build, both in the UK as well as near the proposed SKA site in Western Australia. Next step is the realization of a 400 antenna system. This verification system will consist of one full size station (256 antennas) and three smaller test stations. For correlation of the station signals the Murchison Widefield Array (MWA) back-end will be used.

Key technology development include: wide band antenna, low cost Radio over Fiber (RFoF) and compact high performance signal processing. In SKA1-low signals of all antennas will be digitized, effectively generating a software controlled aperture which can be flexible configured. Allowing correlation rich aperture synthesis, new calibration approaches and very high dynamic range imaging with the sparse array.

Partners in AADC include ASTRON, Cambridge University, ICRAR, INAF, KLAASA, Oxford University and STFC.

9908-149, Session PS3

SAAO’s new robotic telescope and WiNCam (Wide-field Nasmyth Camera)

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The South African Astronomical Observatory (SAAO) is designing and manufacturing a wide-field camera for use on two of its telescopes. The initial concept was of a prime focus camera for the 74-inch Grubb Parsons telescope, where it would employ a 61mmx61mm detector to cover a 23 arcmin field of view. However, while in the design phase, SAAO embarked on the process of acquiring a bespoke 1-metre robotic alt-az telescope with a 43 arcmin field-of-view, which would need a homegrown instrument suite. The prime focus camera design was thus adapted of use on either telescope, increasing the detector size to 92mmx92mm. Since the camera would be mounted on the Nasmyth port of the new telescope, it was dubbed WiNCam (Wide-field imaging Nasmyth Camera). This paper will describe both WiNCam and the new telescope.

Producing an instrument that could be swapped between two very different telescopes posed some unique challenges. At the Nasmyth port of the alt-az telescope there was ample circumferential space, while on the 74-inch the available envelope was constrained by the optical footprint of the secondary to prevent further obscuration. This forced the design into a cylindrical volume of 600mm diameter x 250mm height. The back focal distance was tightly constrained on the new telescope, shoehorning the shutter, filter unit, guider mechanism and a tip/tilt mechanism for the detector into 100mm depth. The iris shutter and filter wheel planned for prime focus could no longer be accommodated. Instead, a compact shutter with a thickness of less than 20mm has been designed in-house, using a sliding curtain mechanism to cover an aperture of 125mmx125mm, while the filter wheel has been replaced with 2 peripheral filter cartridges (6 filters each) and a gripper to move a filter into the beam. We intend using through-vacuum wall PCB technology across the cryostat vacuum interface, instead of traditional hermetic connector-based wiring. This has advantages in terms of space saving and improved performance.

Measures have been taken to minimise the risk of damage during an instrument change. The detector is cooled by a Stirling cooler, which can be disconnected from the cooler unit without risking damage. Each telescope will have a dedicated cooler unit into which the coolant hoses of WiNCam will plug. To overcome an inherent drawback of Stirling coolers, an active vibration damper is incorporated. During an instrument change, the autoguider remains on the telescope, and the filter magazines, shutter and detector package are removed as a single unit.

The new alt-az telescope, manufactured by APM-Telescopes, is a 1-metre f/8 Ritchey-Chrétien with optics by LOMO. The field flattening optics were designed by Darragh O’Donoghue to have high UV throughput and uniform encircled energy over the 100mm diameter field. WiNCam will be mounted on one Nasmyth port, with the second port available for SHOC (Sutherland High-speed Optical Camera) and guest instrumentation. The telescope will be located in Sutherland, where an existing dome is being extensively renovated to accommodate it. Commissioning is expected by mid-2016.

9908-150, Session PS3

Requirement analysis for a modular low resolution spectrograph

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The utility of a high-throughput, low resolution, optical long-slit spectrograph for rapid object classification has been demonstrated with the 2015 deployment of SPRAT, a small single target spectrograph, on the 2.0m Liverpool Telescope (LT). SPRAT, was specifically designed for use on the LT but has generated interested from other observatories wishing to duplicate it. Presented here is a discussion for extending the design of this spectrograph to a produce an adaptable and more compact modular instrument suitable for general deployment to other robotic or manual 2.0m class telescopes. The design uses a common optical/mechanical core to which standard off the shelf optical elements are added to tailor the final desired instrument characteristics. The mechanical and electrical design aim is for a small-footprint, self-contained instrument allowing ease of deployment on the target telescope. To maintain optimal performance in the event of reconfiguration of the optical characteristics an alignment assembly for use between deployments is included as part of the instrument design.

9908-151, Session PS3

OCTOCAM: a fast multi-channel imager and spectrograph proposed for the Gemini Observatory

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OCTOCAM has been proposed to the Gemini observatory as a workhorse imager and spectrograph that will fulfill the needs of a large number of research areas in the 2020s. It is based on the use of high-efficiency dichroics to divide the incoming light in eight different channels, four optical and four infrared, each optimized for its wavelength range. In its imaging mode, it will simultaneously observe a field of 3'x3' in g, r, i, z, Y, J, H, and Ks bands. It will obtain long-slit spectroscopy covering the range between 3700 and 23500 Å with a resolution of 4000 and a slit length of 3 arcminutes. To avoid slit losses, the instrument will be equipped with an atmospheric dispersion corrector operating in the complete spectral range. Thanks to the use of state of the art detectors, OCTOCAM will allow high time-resolution observations and will have negligible overheads in the classical observing modes. It will be equipped with a unique integral field unit that will observe in the complete spectral range with an on-sky coverage of 9.7"x6.8". The integral field uint is based on an image slicer design composed by 17 slitlets, 0.4" wide each. Finally, a state-of-the-art polarimetric unit will allow full Stokes spectropolarimetry in the complete spectral range between 3700 and 22000 Å. In this presentation I will give an overview the optomechanical design of the instrument and will review in detail the most critical and outstanding elements of the project.

9908-152, Session PS3

The new SOXS instrument for the ESO NTT

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SOXS (Son Of X-Shooter) will be a unique spectroscopic facility for the ESO NTT telescope able to cover the optical/NIR band (350-1750 nm), based on the heritages of the X-shooter at the ESO-VLT and of the NOT Transient Explorer (NTE) at the Nordic Optical Telescope. The design foresees a high-efficiency spectrograph with a Resolution-Slit product of 4500, capable of simultaneously observing over the entire band the complete spectral range 350 - 1750 nm with a good sensitivity. The limiting magnitude of R~20-20.5 (1 hr at S/N~10) is suited to study transients identified from on-going imaging surveys. Imaging capabilities in the optical are also foreseen to allow for multi-band photometry of the faintest transients with a field of view of at least 3 arcmin. The instrument has been selected by ESO within the framework of a competitive call for scientific ideas. This paper outlines the status of the project.

9908-153, Session PS3

Design and modeling of a moderate-resolution astronomic spectrograph with volume-phase holographic gratings

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We present a detailed optical design of astronomic spectrograph based on a cascade of volume-phase holographic gratings. The cascade consists of three gratings. Each of them provides moderately high spectral resolution in a relatively narrow range of 83 nm and has low diffraction efficiency outside of the working region. Thus the spectrum image represents three rows, which cover region from 430 to 680 nm without gaps. Wedge-shaped substrates of the gratings allow to center the spectrum rows in the tangential plane and align them in the sagittal plane. A simple triplet lens is used as the collimator and 4-lens all-spherical objective is used in the camera part. Estimated spectral resolving power for 30um-entrance slit is 5300-7900 relative units. The spectrograph overall dimensions are ~755?440?170 mm. Results of diffraction efficiency modeling shows that the required maximum efficiency and spectral selectivity are achievable even when ordinary gratings with quasi-sinusoidal profile recorded on DCG layers are used. For manufacturable grating parameters we obtained estimation of the optical system overall throughput equal to 75% for central wavelengths of each sub-range and about 45% for the seams of sub-ranges. Results of ray tracing in a non-sequential mode demonstrate that stray light introduced by crosstalk of the gratings can be considered as negligible. Further we designed an optical system for coupling of the instrument with an astronomic telescope. The primary mirror diameter was assumed to be 6 m and relative aperture was F/4. The spectrograph can be mounted either in the primary focus or in the Nasmyth focus. For the first case we developed and modeled a 4-fold image slicer, for the second one a combination of 7.8x focal reducer and 6-fold image slicer is designed.

The developed systems allow to work with images with angular size of 0".8 and 1."5 respectively. Finally, tolerance analysis for the spectrograph optical scheme was performed and a concept of instrument's optomechanical design was proposed. Thus we demonstrated that the holographic grating spectrograph has relatively high functional specifications which can give it some advantages in comparison with existing instruments. It's notable for combination of moderately high spectral resolution in a wide region with high throughput (and, subsequently, high sensitivity). In addition, the spectrograph can be built with available manufacturing technologies. We suppose that such spectral instrument would be of special interest for solving of such tasks as investigation of supernovae, low-mass compact objects as white dwarfs, search and investigation of exoplanets etc.

9908-154, Session PS3

Science with OCTOCAM: a new workhorse instrument proposed for Gemini

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OCTOCAM is an 8-channel VIS-IR (g to K-band) imager and medium-resolution spectrograph proposed as new workhorse instrument for the 8m Gemini telescopes. In addition to simultaneous imaging and long-slit spectroscopy it offers additional observing modes of high time resolution, integral-field spectroscopy and spectropolarimetry, making it a very versatile instrument for many science cases in the 2020ies. A special focus of OCTOCAM will be the detection and follow-up of transient sources such as gamma-ray bursts, supernovae, magnetars, active galactic nuclei and yet to be discovered new objects, delivered by large-scale surveys like LSST available in the 2020ies. The diverse nature of transients will require the full range of OCTOCAM capabilities allowing more information in very short time about the source than with any other current instrument and adaptable almost in real time. Another main science topic will be to probe the high redshift Universe and the first stars for which OCTOCAM will be highly suited due to its wide wavelength coverage and high sensitivity. However, OCTOCAM is also suited for a large range of other science cases including transneptunian objects, exoplanets, stellar evolution and supermassive black holes. Our science team comprises more than 50 researchers reflecting the large interest of the Gemini community in the capabilities of OCTOCAM. We will highlight a few important science cases demonstrating the different capabilities of OCTOCAM and their need for the scientific community.

9908-155, Session PS3

The Wendelstein three channel imager (3KK): alignment, commissioning, and first results

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The Ludwig-Maximilians-Universität München operates an astrophysical observatory on the summit of Mt. Wendelstein which was equipped with a modern 2m-class robotic telescope in 2011 (see Hopp et al, #7733, #8444, #9145).

One of the two Nasmyth ports is designed to deliver the excellent (<0.8" median) seeing of the site for a FoV of 60 sqarcmin without any corrector optics at optical and NIR wavebands. This port hosts a three channel imager where the design was already presented in Lang-Bardl et al, #7735. It will mainly be used for observations of targets of opportunities like Gamma-Ray-bursts or efficient photometric redshift determination of sources identified by surveys like PanSTARS, Planck (SZ) or eROSITA. The covered wavelength range is 340 nm to 2.3 microns. The camera provides standard broadband filters (Sloan, Y, J, H, Ks) and 5 narrowband filters (BrGamma, H2, OI, Halpha, SII).

We will present the final design of the camera, the assembly and alignment procedure performed in the laboratory before we transported the instrument to the observatory. We will also show first results of the achieved on sky performance concerning image quality and efficiency of the camera in the different filter passbands.

9908-156, Session PS3

Gamma/hadron separation in HAWC using neural networks

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The High Altitude Water Cherenkov (HAWC) Observatory is a ground based air-shower array of 300 water Cherenkov detectors (WCDs) located on the slope of Volcan Sierra Negra, Mexico. Each WCD has 4 photonmultipler tubes (PMTs) that detect secundary particles of air-showers produced by gamma-rays and cosmic rays (CRs). Those CRs are the main problem in the gamma-ray sources analysis, therefore, we need to separate between both particles. Currently, the HAWC data is divided in 10 bins that depend on the number of PMTs activated in each event. For the supression of CRs background, HAWC uses two variables, Compactness and PINCness, that are used to apply a simple cutoff in each bin. In this work we trained a neural network (NN) that uses these two variables as input parameters in oder to obtain one output parameter and use it as a cutoff. We used simulated proton and gamma events to train the NN and we found an optimal cutoff, that we applied to the Crab Nebula. This work predicts a better gamma/hadron separation in some bins when we use Monte Carlo (MC) data.

9908-157, Session PS3

The prototype cameras for trans-Neptunian automatic occultation survey

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The Transneptunian Automated Occultation Survey (TAOS II) is a three robotic telescope project to detect the stellar occultation events generated by TransNeptunian Objects (TNOs). TAOS II project aims to monitor about 10000 stars simultaneously at 20Hz or higher to enable statistically significant event rate. The TAOS II camera is designed to cover the 1.7 degree diameter field of view of the 1.3m telescope with 10 mosaic 4.5k?2k, 16 micron pixel CMOS sensors. The new CMOS sensor (e2v CIS 113) has a back illumination thinned structure and high sensitivity to provide similar performance to that of the back-illumination thinned CCDs. Due to the requirements of high performance and high speed, the development of the new CMOS sensor is still in progress.

Before the science arrays are delivered, three prototype cameras are developed to help on the commissioning of the robotic telescope system. The prototype cameras use the small format e2v CIS 107 devices but with the same dewars for the TAOS II science camera. CIS 107 sensor is a device for development purpose with 10 different variations of pixel designs. The control clocks of CIS 107 are very similar to the control signal for CIS 113 devices. The sensor has 1500 x 2000, 7 micron pixels with 4 outputs. Each variation covers 1500 x 200 pixels. The 4T pixels are with high resistivity epitaxial silicon and back thinned to 11 microns. At 200K, the device shows peak QE higher than 90%, readout noise around 4e- and dark current <0.1e-/s/pix.

Two prototype cameras have only one sensor at the center of focal plane while the third camera has 5 sensors to assess the optical quality of the telescope at the field edge. The sensors, mounted on a single Invar plate, are cooled to the operation temperature of about 200K by a cryogenic cooler. The Invar plate is connected to the dewar body through a supporting ring with three G10 bipods.

The control electronics consists of analog part and a Xilinx FPGA based digital circuit. One FPGA is needed to control and process the signal from CIS 107. For each field star, 7?7 pixels box will be readout at 20Hz, up to 40Hz. The pixel rate for each channel is about 1Mpix/s. The FPGA module also calculates the total flux and also the centroid coordinates for every field star in each exposure. For the camera with five sensors, a vacuumed sealed PCB is used to pass the signals outside of the vacuum dewar. A synchronization circuit between each FPGA and each camera is also provided to ensure the exposure duration error of each sensor to be within 1ms.

In this report, the performance of the prototype cameras will be presented. The status of the CIS 113 sensors will also be covered.

9908-158, Session PS3

Acousto-optical imaging spectropolarimeter

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Imaging spectropolarimetry provides information about distribution of light polarization in astrophysical objects both in spectral and spatial domains. Polarization of the radiation is observed in a variety of astronomical objects: AGN and quasars, circumstellar envelopes of the symbiotic stars, supernova remnants, star-forming regions, planetary and protoplanetary nebulae. Polarization often strongly depends on the wavelength of light. By means of the spectral polarimetric observations we can obtain the information about the spatial structure of objects and magnetic fields in them.

Acousto-optic tunable filters (AOTFs) are used as tunable monochromators with wide angle aperture for HSI. An AOTF is sensitive to polarization of light, and in common HSI applications linear polarizers are used before and after AOTFs. Thus, the image intensity corresponds to projection of light polarization to one axis which is either parallel or perpendicular the diffraction plane. A single AOTF can also be used for spectropolarimetry when a special optical system is used (V.Ya. Molchanov et al., Proc. SPIE, V. 9147, P. 91472T, 2014; S.P. Anikin et al., Pat. RU 2569907 C1, filed 28.08.2014) . In September 2015, we commissioned an imaging spectropolarimeter based on a single AOTF at the 0.6-meter telescope of the SAI Crimean Station in Nauchny. During observations, we discovered some of its disadvantages: asymmetric transfer function of this configuration reduces the throughput and causes noticeable spectral artifacts for beams with focal ratio higher than F/20. That inspired us to design a spectropolarimeter that is free of these drawbacks.

The prototype of the new instrument uses two similar AOTFs consequently. Each of them operates in a noncritical phase matching (NPM) geometry, but the Bragg angles for two filters correspond to different polarizations. As the result, two diffracted beams after the AOTFs are parallel to each other. Further, the beams are separated by means of the Wollaston prism and imaged with the relay optical system. The transfer function of the AOTFs in NPM geometry is almost circularly symmetric and the acceptance angle is suitable for the beams with F/10 focal ratio. The spectropolarimeter can be used without modifications at 1-meter and 2-meter class telescopes. Spectral range of the device can cover an octave-spanning band within the range of 370 – 3500 nm. In the report, we compare the performance of the designed two-stage spectropolarimeter with that of the previous single-AOTF configuration.

9908-159, Session PS3

GCT: an end-to-end Schwarzschild-Couder telescope prototype for the Cherenkov Telescope Array

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The Cherenkov Telescope Array (CTA) project aims to build the next generation ground-based Very High Energy imaging Cherenkov instrument. It will be devoted to the observation of gamma rays over a band of energy, from ~20 GeV to above 100 TeV. Given this wide energy range, three size classes of telescopes with different mirror areas are foreseen to cover the low, intermediate and high-energy domains. Among them, the Small Size Telescopes (SSTs) are devoted to the highest energy range, becoming most sensitive from 5 TeV to above 100 TeV. At these energies, the limiting factor is not the number of Cherenkov photons produced in the extended air shower, but rather the number of showers observed. Therefore, the SSTs, though possessing a modest mirror diameter of about 4 m, will be spread over an area greater than about 4 km2, to maximise the effective area of the array.

GCT (Gamma-ray Cherenkov Telescope) is an Australian-Dutch-French-German-Japanese-UK-US sub-consortium of CTA, currently building a dual-mirror prototype for the SSTs. The telescope is based on a Schwarzchild-Couder (SC) optical design, an innovative solution for ground-based Cherenkov astronomy, which allows a compact telescope structure, a lightweight large field-of-view camera and enables good angular resolution across the entire field-of-view (FoV).

The telescope mechanical structure was designed with the philosophy to provide a lightweight, simple and compact structure compatible with CTA specifications in terms of stiffness, cost or lifetime; to decrease manufacturing costs by using commercial-off-the-shelf modules and similar systems in the telescope; and to ease the assembly and maintenance phases. The optical structure consists of two metallic lightweight mirrors and a camera. Two prototype cameras will be tested on the prototype structure. These two cameras have a similar physical size and weight (about 50 kg), a curved focal plane and a diameter of roughly 45 cm, instrumented with 2048 pixels. With a pixel FoV of ~0.2°, the camera's total FoV is about 9°. They differ only by the photosensors used since the first camera prototype uses MultiAnode Photo-Multipliers tiles whereas the second one uses Silicon Photo-Multipliers tiles. The cameras are designed to record the very fast flashes (about tens of nanosecond) of Cherenkov light produced in the atmosphere from gamma-initiated electromagnetic showers. The telescope was assembled from April to November of 2015. On-site tests and measurements with the first prototype camera began at the end of 2015.

This paper reviews the different components of the telescope, from mechanics and optics to the telescope control system, and presents the first on-sky measurements made with the telescope. Plans for the pre-production and the CTA production in the next years are also discussed.

9908-160, Session PS3

The GMOX science case: resolving galaxies through cosmic time

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We present the key scientific questions that can be addressed by GMOX, a Multi-Object Spectrograph selected for feasibility study as a 4th generation instrument for the Gemini telescopes. Using commercial digital micro-mirror devices (DMDs) as slit selection mechanisms, GMOX can observe hundred of sources at R~5000 between the U and K band simultaneously. Exploiting the narrow PSF delivered by the Gemini South GEMS MCAO module, GMOX can synthesize slits as small as 40mas reaching extremely faint magnitude limits, and thus enabling a plethora of applications and innovative science.

Our main scientific driver in developing GMOX has been "Resolving galaxies through cosmic time": GMOX at GeMS can take spectra of regions as small as 300 pc at redshift 1.5. At lower or higher redshift, where the angular diameter distance decreases, GMOX can resolve even smaller regions, allowing us to probe the growth and evolution of galaxies with unprecedented detail throughout the History of the Universe. GMOX's multi-object capability and high angular resolution enable efficient studies of crowded fields, such as the Milky Way globular clusters and bulge, the Magellanic Clouds, Local Group dwarf galaxies and galaxy clusters.

The wide-band simultaneous coverage and the very fast slit configuration mechanisms also make GMOX ideal for followup of LSST transients.

9908-161, Session PS3

PRAXIS: a near-infrared spectrograph optimised for suppression of the OH background with fibre Bragg gratings

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The problem of atmospheric emission from OH molecules is a long standing problem for near-infrared astronomy.

PRAXIS is a unique spectrograph, currently in the build-phase, which is fed by a fibre feed that removes the OH background. The OH suppression is achieved with fibre Bragg gratings, which were tested successfully on the GNOSIS instrument. PRAXIS will use the same fibre Bragg gratings as GNOSIS in the first implementation, and new, cheaper and more efficient, multicore fibre Bragg gratings in the second implementation. The OH lines are suppressed by a factor of ~1000, and the expected increase in the signal-to-noise in the interline regions compared to GNOSIS is a factor of ~9 with the GNOSIS gratings and a factor of ~17 with the new gratings.

PRAXIS will enable the full exploitation of OH suppression for the first time, which was not achieved by GNOSIS due to high thermal emission, low spectrograph transmission and high detector noise. PRAXIS will have extremely low thermal emission, through the cooling of all significantly emitting parts, including the fore-optics, the fibre Bragg gratings, a long length of fibre, and the fibre slit, and an optical design that minimises leaks of thermal emission from outside the spectrograph. PRAXIS will achieve low detector noise through the use of a Hawaii-2RG detector, and a high throughput through a efficient VPH based spectrograph.

PRAXIS will determine the absolute level of the interline continuum and enable observations of individual objects via an IFU. PRAXIS will first be installed on the AAT, then later on an 8m class telescope.

9908-162, Session PS3

Update on BOMBOLO: a 3-arm, wide-field, near-UV/optical imager for the 4-meter SOAR telescope

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BOMBOLO is our instrument proposal for covering a series of scientific cases, in the not-so-explored time window of tens of seconds to minutes exposures, to be installed at SOAR observatory. BOMBOLO is a wide field imager, capable of simultaneous, synchronous and independent observations in three different bands of the near-UV and visible wavelengths.

BOMBOLO will be located at one of the Bent Cassegrain focal stations. Given its length, weight and mounting limitations, we discuss the current mechanical and opto-mechanical design of the instrument, given flexures caused by a changing gravity vector. In order to validate our designs, a Monte-Carlo simulation is used to explore different observing conditions, as the starting point for static and dynamic studies of the structure using FEA tools.

A quick update on the current state of the instrument related to the optical design and manufacturing as well as the CCD cameras is included.

9908-163, Session PS3

LRS2: design, assembly, testing, and commissioning of the second-generation low-resolution spectrograph for the Hobby-Eberly Telescope

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The second generation Low Resolution Spectrograph (LRS2) is a new facility instrument for the Hobby-Eberly Telescope (HET). Designed as a powerful spectroscopic follow-up platform, LRS2 is based on the design of the HET's new Visible Integral-field Replicable Unit Spectrograph (VIRUS) and provides integral field spectroscopy for two seeing-limited fields of 6x12 arcseconds with unity fill factor. The replicable design of VIRUS has been leveraged for LRS2 to gain broad wavelength coverage from 370 nm to 1.0 micron, spread between two fiber-fed dual-channel spectrographs that operate in unison but observe independent fields that are separated by 100 arcseconds. The blue spectrograph pair, LRS2-B, covers 364 - 467 nm and 454 - 700 nm at fixed spectral resolving powers of ~2500 and ~1400, respectively, while the red spectrograph pair, LRS2-R, covers 643 - 845 nm and 823 - 1056 nm with both of its channels having spectral resolving powers of ~2500. In this paper, a detailed description of the instrument's design, assembly, and laboratory testing is provided in which the focus is placed on the departures from the basic framework of the design and processes previously established for VIRUS. Both LRS2 spectrograph pairs have been successfully deployed on the HET, and commissioning efforts are ongoing. Using on-sky data, the performance of the spectrograph is compared to models of the instrumental sensitivity. The measured performance of LRS2 indicates that the instrument will provide efficient spectroscopic follow-up observations of individual targets, and will be especially powerful when combined with the extensive survey capabilities of VIRUS for HETDEX.

9908-164, Session PS3

Cryogenic near infrared spectropolarimeter for the Daniel K. Inouye Solar Telescope

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The Cryogenic Near Infrared Spectropolarimeter (CryoNIRSP) is a first light instruments for the Daniel K Inouye Solar Telescope (DKIST). This dual-beam instrument is designed to sensitively measure the full polarization state (Stokes I, Q, U and V) of solar spectral lines at wavelengths from 1 μm (500 nm goal) to 5 μm. The high dynamic range of the instrument allows measurements of the solar disk, near-limb and faint corona where the near-limb and coronal observations depend on DKIST's coronagraphic capabilities. It has the widest field-of-view and longest wavelength coverage of the four first-light DKIST facility instruments. These capabilities will provide sensitive measurements of the solar disk in the carbon monoxide (CO) bands; unique observations of spicules, prominences, flares and eruptive events in the low corona; and unprecedented sensitive measurements of the coronal magnetic field.

The CryoNIRSP instrument is divided into three optical subsystems: the feed optics, the spectrograph and the context imager.

The room temperature feed optics directs the light to 1) the spectrograph only 2) the context imager only 3) the spectrograph and context imager simultaneously. It also provides means to scan the field of view across the spectrograph slit, includes calibration lamps and accommodates the polarization modulator.

The spectrograph is an all reflective design to provide high overall throughput and broad spectral coverage. A 408 mm wide R2 echelle grating is required to achieve the desired resolution at the longest wavelengths. In order to reduce the thermal background for the IR

observations, we use closed helium cycle cryo-coolers to cool the filters, imaging optics, grating, polarization analyzer and detector to 77 K. The spectrograph will operate in a high resolution (R=100,000) disk mode and a low resolution (R=30,000) coronal mode with spatial resolutions of 0.15 and 0.5 arcsec and fields of view of 1.5 x 1.5 and 4 x 3 arcmin respectively. A multi-slit operation mode is also available that efficiently uses detector pixels for large area single-line spectropolarimetry.

The context imager is a separate optical system that records a 100 x 100 arcsec field around the slit at wavelengths of coronal emission lines of interest. The feed optics scan mirror can be used to mosaic the whole coronal mode field of view. The bandpass filters and detector inside the imager are cooled to cryogenic temperatures as well.

Both, spectrograph and context imager use a 2048 x 2048 HAWAII 2 array produced by Teledyne Scientific & Imaging. The PB1HS array controller was developed at the University of Hawaii, Institute for Astronomy in Hilo. This new controller reads the H2RG in slow and fast mode and allows for external triggering which is essential for synchronization to the polarization modulator.

CryoNIRSP has been fully assembled and initial laboratory tests were performed. This paper discusses the CryoNIRSP design and lessons learned during cryo-mechanical, grating rotation stage, and polarization analyzer sub-assembly testing.

9908-165, Session PS3

Balloon UV experiments for astronomical and atmospheric observations

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The near-ultraviolet (NUV) window from 200 to 400 nm has been largely unexplored through balloons for astronomy. This window includes several lines important to atmospheric chemistry (eg. SO2, O3, HCHO,BrO). We discuss the development of a compact near ultraviolet spectrograph with fibre optics input for balloon flights. It is a modified Czerny-Turner system using off the shelf optics. The system is portable and scalable to different telescopes. The use of reflecting optics reduces the transmission loss in UV. It uses an image intensified CMOS sensor operating in photon counting mode as the detector of choice. A light weight pointing system which have been developed for stable pointing of astronomical sources will also be discussed, together with methods to improve it's accuracy like using in-house build star sensor etc. Our primary scientific objectives include the observation of bright solar system objects like visible eye comets, moon and planets. The studies of planets will give us valuable information about the aurorae of planets, this will help us model and compare atmosphere's of other planets and earth. The other major objective is to look at the diffuse ultraviolet atmospheric emission features (airglow lines) and column densities of trace greenhouse gases, A spectrograph helps us in simultaneous measurement of various trace gases as well as provide better accuracy at higher altitudes compared to electromechanical trace gas measurement sondes. These lines contaminate most astronomical observations but are poorly characterized. Other objectives will include sprites in the atmosphere and meteor flashes from high altitude burn-outs. Our recent experiments and observations with high altitude balloons will be discussed.

9908-166, Session PS3

Development of high reflectivity coatings for large format Fabry-Perot etalons

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The Visible Tunable Filter (VTF) is a diffraction-limited narrowband tunable instrument for imaging spectropolarimetry in the wavelength range between 520 and 860 nm. It is based on large-format Fabry Perots. The instrument will be one of the first-light instruments of the 4m aperture Daniel K. Inoue Solar Telescope (DKIST) that is currently under construction on Maui (Hawaii).

To provide a field of view of 1 arcmin and a spectral resolution ?/?? of about 100.000, the required free aperture of the Fabry Perots is 240mm. The high reflectivity coatings for the Etalon plates must preserve the plate figure specifications of better ?/100, and a micro roughness of < 0.1nm rms.

Coated surfaces with similar specifications have successfully been made for reflecting mirrors on thick substrates but not for larger format Fabry-Perot systems. Ion Beam Sputtering (IBS) based coatings provide stable, homogeneous, and smooth coatings. But IBS coatings also introduce stresses to the substrate that influence the plate figure in our case at the nm level.

In a joint effort with a industry partner and a French CNRS research laboratory, we developed and tested processes on small and full size substrates, to provide coated Etalon plates to the required specifications. Zygo Extreme Precision Optics, Richmond, CA, USA, is polishing and figuring the substrates, doing the metrology and FE analysis. LMA (Laboratoire Matériaux Avancés, Lyon, France) is designing and making the IBS coatings and investigating the detailed behavior of the coatings and related processes. Both partners provide experience from manufacturing coated plane optics for gravitational wave detection experiments and EUV optics. The Kiepenheuer-Institut für Sonnenphysik, Freiburg, Germany is designing and building the VTF instrument and is leading the coating development.

We present the characteristics of the coatings and the substrate processing concept, as well as results from tests on sample size and from full size substrate processing. We demonstrate that the tight specifications for a single Etalon plate are reached.

9908-167, Session PS3

The PAU Camera carbon fiber cryostat and filter interchange system

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The PAU Camera is a novel instrument designed to make studies of Dark Energy. It is equipped with a system of 40 narrow-band (12.5 nm wide in spots of 10 nm) filters spanning the wavelength range from 450 nm to 850 nm, and with 6 wide-band filters (u, g, r, i, z, Y). It aims at observing ~100 deg2 of sky and provide up to 3 million redshifts to i(AB)~22.5 with

a z-uncertainty of ~ 3 per mill, in which shape and deep Broad-Band photometric measurements have already been obtained by CFHTLenS and KIDS, an in which spectroscopic redshifts for calibration are available from the GAMA, VIPERS, DEEP2 and zCOSMOS redshift surveys. The survey will be a few magnitudes deeper than current completed large flux limited surveys (such as Gamma) and 10 times larger than current completed deep flux limited surveys (such as VVDS/VIPERS/Deep2).

The camera is installed at the William Herschel Telescope. The focal plane, composed of 18 Hamamatsu photonics 2k x 4 k 200 microns thick fully depleted CCD's covers ~1 deg2 FoV, every 15 micron pixel corresponding to 0.26''. The PAU Camera is a technologically pioneer instrument built with a large carbon fiber enclosure in order to minimize weight at the WHT prime focus. Since the 8 central CCd's cover the observation of the 40 Narrow Band filters, a system of five movable filter trays arranged in juke-box like mechanism is installed. In order to minimize the dead areas in the focal plane, the filter trays are located as close as possible to the CCD's inside the cryostat. The cryogenic system includes a dual system: a Nitrogen system to make a fast cool down during installation of the instrument and a cryocooler system to maintain the operational temperature during the observations. The device operates within the range of temperatures from 150K to 300K at the absolute pressure of 10-7 mbar, being class-100 compliant.

A description of the challenges of having the largest carbon fiber cryostat in a camera of tis characteristics and its movable non accessible movable tray system is given, together with the experience in commissioning and operating such systems in the WHT telescope during the last year, since the camera was first installed in June 2015.

9908-168, Session PS3

Qualification of HEIDENHAIN linear encoders for picometer resolution metrology

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The Visible Tunable Filter (VTF) is a narrowband tunable instrument for imaging spectropolarimetry in the wavelength range between 520 and 860 nm. It is based on large-format Fabry Perots with a free aperture of 240mm. The instrument will be one of the first-light instruments of the 4m aperture Daniel K. Inoue Solar Telescope (DKIST) that is currently under construction on Maui (Hawaii).

To provide stable and repeatable spectral scanning by tuning the air gap distance of the Etalons, a metrology system with 20 pm resolution and drift stability of better 100 pm per hour is needed. The integration of the metrology system must preserve the tight optical specifications of the Etalon plates.

The HEIDENHAIN LIP 382 linear encoder system has a selected linear scale for low noise high signal interpolation. The signal period is 128nm and the interpolated signal from the sensor can be read out at 128nm/14bit = 7.8125pm.

To qualify the LIP 382 system for the VTF, we investigated the resolution and stability under nominal VTF operation conditions and verified a mounting concept for the sensor heads.

We present results that demonstrate that the LIP 382 system fulfills the requirements for the VTF Etalons. We also present a design for the sensor head mounts.

9908-169, Session PS3

MOPTOP: a multi-colour optimised optical polarimeter

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We present the design and science case for a fourth-generation polarimeter; MOPTOP: a Multicolour OPTimised Optical Polarimeter which is optimised for sensitivity and bi-colour observations. Its location on the world's largest fully autonomous robotic telescope, the Liverpool Telescope (LT), will allow it to become the community's most powerful instrument for probing transient astronomical sources such as powerful gamma-ray bursts, blazars and X-ray binaries. It will enable the first measurements of dust production rates and surface composition in a large sample of solar system objects currently being discovered by the ESA Gaia space mission.

Building on the scientific success of the predecessor polarimeter, RINGO, we introduce an optimised polarimeter which is only limited by the photon counting efficiency of the detectors. Using a combination of four CMOS cameras, a continuously rotating half-wave plate and a wire grid polarizing beamsplitter, we can accurately measure the polarisation of sources down to ~19th magnitude with much lower systematics (<0.1%) and variability timescales as short as a few seconds. This will allow accurate measurements of the intra-nightly variability of the polarisation of sources such as gamma-ray bursts and blazars (AGN orientated with the jet pointing toward the observer), allowing the constraint of magnetic field models revealing more information about the formation, ejection and collimation of jets.

Although the MOPTOP design was produced for the specifications of the LT, we also intend the instrument design to be fully accessible to the public domain and we encourage copies to be placed on other facilities to allow better sampling of transient sources.

9908-170, Session PS3

The PAUCam readout electronics system

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The PAUcam is an optical camera with a wide field of view of 1 deg x 1 deg and up to 45 narrow and broad band filters. The camera is already installed on the William Herschel Telescope (WHT) in the Canary Islands, Spain and successfully commissioned during the first period of 2015.

The camera is composed of a mosaic of 18 scientific-grade Hamamatsu Photonics CCDs type S10892-04, 2k x 4k pixels, back-side illuminated and fully depleted. The CCDs configuration can be changed on-the-fly by software to use the whole focal plane for science (normal mode) or to use the top and bottom CCDs as guiders (guider mode). The readout speed for the science mode is 150 KHz and for guiding mode, the readout speed can be increased up to 300 KHz while reading one region of interest (ROI).

In order to fulfill with the specifications for the camera readout system, there was necessary to use four MONSOON (NOAO) crates: two of them reading out eight CCDs each one and the other two crates reading out just one CCD per crate in order to reach different speeds and exposure times for guiding issues. There is also involved a preamplification stage (PREAMP), one per CCD, located inside the camera cryostat, so it was designed to be suitable for low outgassing and reduced power consumption/dissipation. The fan out boards (MIX) connect signals from

the inner PREAMP stage to the MONSOON crates trough a DSUB50 hermetic feedthrough connector and they are able to drive up to 5 CCDs signals for the long size MIX's pcb and up to 3 CCDs for the short one.

The camera is mounted on the primary focus and due the limited weight supported by the telescope at this point, there was necessary to mount the whole readout electronics power supplies at the nasmyth level which required more than 30 meters of cables to connect the front-end and demanding a dedicated filter stage to stabilize the power supplies and to guarantee the required low noise power sources.

Besides that, there was necessary to avoid any uncontrolled grounding loop around the readout electronics system since the camera is equipped with several servo-motors, pumps and cryocoolers controlled by a PLC, then on this way and from the very beginning, the camera design was conceptually focused to a "star-ground" configuration with enough flexibility to be adapted to the telescope conditions.

Finally and during the camera commissioning, there were performed some standard tests using dome flats and then the validation on sky showed the good performance of the whole readout electronics system with a mean readout noise of ~9 e- rms which main results are presented on this paper.

9908-171, Session PS3

Characterization and performance of PAUCam filters

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PAUCam is a large field of view camera designed to cover the full useful field in the corrected prime focus of the William Herschel Telescope (WHT), at the Observatorio del Roque de los Muchachos (La Palma, Canary Islands, Spain). To cover this field of view, 18 CCD detectors of 2K ? 4K and 15 ?m of pixel size, manufactured by Hamamatsu Photonics K. K., are distributed in a square of 20 ? 20 cm, with a pixel scale of 0.265 arcsec/pix.

The main purpose of this camera is to create a low resolution spectrum (R ~40–80) for all objects in the field of view up to magnitude 22.5. The camera has five trays, each with eight different narrow band filters, placed in front of the eight central detectors. The rest of the CCDs are covered with broad band filters for calibration and/or guiding. Six additional trays with six large broad band filters cover the full focal plane.

In this contribution, we describe the performance of these filters both in the characterization tests at the laboratory and on-site.

The large broad band filters were manufactured by Asahi Spectra Co. Ltd. covering the photometric bands of DECam (at NOAO's Blanco Telescope): u, g, r, i, z and Y. The physical size of these filters is 203.4 mm ? 208.8 mm ± 0.1 mm with a chamfer of 3.0 mm and a thickness of 3.0 ± 0.1 mm. The difference transmission in the filter surface at a given wavelength is up to 1%, and the transmission out-of-band is smaller than 1%. The acceptance and post-calibration tests were carried out at the IFAE laboratories determining the transmission in different points of the filter with a good agreement with the expected profiles.

The narrow band filters, and the small broad band filters were manufactured by the Iridian Spectral Technologies. In this case, the physical size of each filter is 65.7 mm ? 33.8 mm ± 0.1 mm, with a thickness of 3.0 ± 0.1 mm, and the rectangular profile of each one, with a FWHM of 14 nm are centered in the range between 455 and 845 nm in steps of 10 nm. The small filters, narrow and broad-band, were tested at the CIEMAT laboratories using a spectrophotometer and measuring the filters in eighteen positions with an excellent agreement with the profiles design.

All filters are placed within a few millimeters from the focal plane in a focalized beam. This produces a change the effective transmission profile. On the other hand, the incidence's angle changes, radially in the focal plane, between 0º in the center up to 3º in the external filters. Moreover, the filters are operating in vacuum at 240K, which produces a small shift in the wavelength. All of these effects are more important for the narrow band filters than for the broad band ones for which they can be neglected.

The first light of PAUCam was in June 2015, the commissioning of the camera confirming its expected performance.

9908-172, Session PS3

PLC-controlled cryostats for the BlackGEM detectors

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BlackGEM is an array of wide-field telescopes, currently under development at the Radboud University Nijmegen and at NOVA (Netherlands Research School for Astronomy). It targets the detection of the optical counterparts of gravitational waves. The first three BlackGEM telescopes are planned to be installed in 2017 at the La Silla observatory (Chile). A single prototype telescope, named MeerLICHT, will already be commissioned by the end of 2016 in Sutherland (South-Africa) to provide an optical complement for the MeerKAT radio array. The BlackGEM array consists of, initially, a set of three identical Dall-Kirkham Cassegrain telescopes with a 65-cm primary mirror in a carbon fiber structure. Each telescope is equipped with a single STA1600 CCD detector with 10k x 10k 9-micron pixels that covers a 2.7 square degrees field of view. The cryostats for housing these detectors are developed and built at the Institute of Astronomy of the KU Leuven University (Belgium).

The operational model of BlackGEM requires long periods of reliable hands-off operation. Therefore, we designed the cryostats for long vacuum hold time and we make use of a closed-cycle cooling system, based on Polycold PCC Joule-Thomson coolers. A single programmable logic controller (PLC) controls the cryogenic systems of several BlackGEM telescopes simultaneously, resulting in a highly reliable, cost-efficient and maintenance-friendly system. PLC-based cryostat control offers some distinct advantages, especially for a robotic facility. Apart of temperature monitoring and control, the PLC also monitors the vacuum quality, the power supply and the status of the PCC coolers (compressor power consumption and temperature, pressure in the gas lines, etc.). Furthermore, it provides an alarming system and safe and reproducible procedures for automatic cool down and warm up. The communication between PLC and higher-level software takes place via the OPC-UA protocol, offering a simple to implement, yet very powerful interface. Finally, a touch-panel display on the PLC provides the operator with a user-friendly and robust technical interface. In this contribution, we present the design of the BlackGEM cryostats and of the PLC-based control system.

9908-173, Session PS3

Innovative polarization-holographic imaging Stokes spectropolarimeter for astronomy: first results of laboratory and field tests

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An innovative real-time imaging Stokes spectropolarimeter is presented. The main unit of the polarimeter is an integral polarization-holographic diffraction element, which enables the complete analysis of the polarization state of light to be carried out in real time. An element is recorded by a special holographic schema using circularly and linearly polarized beams. As a result it decomposes an incoming light into orthogonal circular and linear diffraction orders.

The simultaneous CCD intensity measurements of the corresponding points or areas in the diffraction orders and further data reduction through the calibration parameters we get real-time Stokes images of a light source. The further reduction of Stokes images allows to determine detailed polarization state of a light coming from a point or extended space object in a narrow or a wide spectral range.

The operating spectral range of the polarimeter is 500-1600 nm with diffraction efficiency equal to 20% at 532 nm, 16% at 635 nm and 2% at 1550 nm.

The laboratory calibration tests were obtained with a quasi-monochromatic point size depolarized light source which further were circularly or linearly polarized with known polarization parameters and a degree of polarization near to 100%.

The theoretical model of relations between measured intensities in different diffraction orders and Stokes parameters, earlier developed by the authors (Kilosanidze B., Kakauridze G. SPIE Proceedings, vol. 8082-126, 2011), were used to calibrate the polarimeter for different spectral ranges. The laboratory tests show that the resulting errors are near of 1% or better.

For field test the polarimeter were installed on the f/10 refractor with 10cm aperture and CCD autoguiding. The bright polarization standard stars and the selected areas of moon with known polarization were observed through different light filters during several nights. Further reduction confirms the results of laboratory tests and ability of this new polarimeter to successfully be used for under 1% accuracy polarimetry. The possibility of increasing the accuracy by one order is discussed. The polarimeter is very compact, light weight and could be installed both on ground-based large or small and airborne telescopes.

9908-174, Session PS3

End-to-end simulations of the visible tunable filter for the Daniel K. Inouye Solar Telescope

Wolfgang Schmidt, Matthias Schubert, Jörg Baumgartner, Alexander Bell, Andreas Fischer, Clemens Halbgewachs, Frank Heidecke, Thomas J. Kentischer, Oskar F. von der Lühe, Thomas Scheiffelen, Michael Sigwarth, Kiepenheuer-Institut für Sonnenphysik (Germany)

The Visible Tunable Filter (VTF) is a narrowband tunable filter system for imaging spectroscopy and spectropolarimetry based on large-format Fabry Perot Etalons. The instrument will be one of the first-light instruments of the Daniel K. Inouye Solar Telescope (DKIST) that is currently under construction on Maui (Hawaii). The VTF is being developed by the Kiepenheuer Institut fuer Sonnenphysik in Freiburg, as a German contribution to the DKIST.

We perform end-to-end simulations of spectropolarimetric observations with the VTF to verify the science requirements of the instrument. The instrument simulator includes the two Etalons in telecentric configuration, illuminated by an f:200 beam, and prefilters for different wavelength bands with widths between 0.4 and 0.8 nm.

The clear aperture of the Etalons is 250 mm, corresponding to an angular field of view with a diameter of 60 arcsec. The detectors in the focal plane have a resolution of 0.014 arcsec. The instrument simulator takes into account that the two Etalons are indeed not exactly in telecentric configuration (i.e., mounted in a focal plane), but are displaced from the focal plane by about 500 mm each. The micro-roughness of the Etalon is included in the simulations, as well as large-scale figure errors of the plates. We use an ideal modulator with equal modulation coefficients of 3-1/2 for the polarization modulation.

The micro-roughness of the Etalon's high-reflectivity coatings was measured to 0.095 nm RMS on a full-size prototype plate. This value is included in the simulations. To model the large-scale figure errors we employ low-order Zernike polynomials (power and spherical aberration) with amplitudes of 2.5 nm RMS.

We synthesize Stokes profiles of two neutral iron lines (630.15 nm and 630.25 nm) for a range of magnetic field values and for several inclination angles using the SIR code. We estimated the photon noise on the basis of the DKIST and VTF transmission values, the atmospheric transmission and the spectral flux from the Sun. For the simulations, we employ a signal-to-noise ratio of SNR=675, a typical value for VTF measurements.

To determine the magnetic field sensitivity, we performed a spectral inversion of the simulated observations and compared the resulting values for the magnetic field strength with the input values. We obtain a sensitivity of 20 G for the longitudinal component and for 100 G for the transverse component, in agreement with the science requirements for the VTF.

9908-175, Session PS3

Bokeh mirror alignment for Cherenkov telescopes

Sebastian Achim Mueller, ETH Zürich (Switzerland)

Segmented reflectors are a great choice for Imaging Atmospheric Cherenkov Telescopes (IACTs). They are light weight and mass produced. Huge and fast apertures of segmented reflectors provide good image quality to recognize the few gamma ray air showers in the vast majority of cosmic ray showers.

However, the alignment of the individual mirror facets of an segmented reflector remains a challenge. We present a new alignment method which is using the Bokeh of the imaging reflector.

Every non zero aperture imaging system has a non trivial Bokeh function. In case of thin imaging systems, the Bokeh function is very close related to the aperture function of the system. The Bokeh function of any imaging system can be observed when recording images with this system of a point like light source in an out of focus configuration.

On segmented reflectors, the aperture function shows special features because of the gaps in between the mirror facets. In approximation of thin apertures, the Bokeh function turns out to fit the aperture function up to a scaling factor which depends on the object and image sensor distance. Therefore also the Bokeh function of a segmented reflector shows the special features of the segmented aperture.

But, the Bokeh function only matches the aperture function when the mirror facets are well aligned which marks the starting point for Bokeh alignment.

Bokeh alignment is a more general form of the 2f alignment where a light source in distance 2f is observed to align the facets. We observe

and optimize the Bokeh of a segmented reflector to determine the facet orientations and to align the mirror facets. We create templates for the desired Bokeh function of our reflector and make the facet orientations match these. A first template can be obtained very easy by taking a picture of the segmented reflector aperture function, scale it, and make it the Bokeh template.

A more precise Bokeh template, which overcomes the limitations of the thin aperture approximation, is taken from ray tracing simulations.

Bokeh alignment can be done any time and does not need star light or clear sky.

When a flash light is used to observe the Bokeh, it can even be done during the day. Bokeh alignment is geometrically much more flexible then 2f alignment. It can reach the inner most facets of a reflector more easily, and it can be done off axis. Further, the orientation determination of the mirror facets can be done very fast, since the alignment of the facets can be deduced from a single Bokeh record. Bokeh alignment scales better with the number of facets then methods observing star images which have to use their facet actuation extensively to overcome the image to facet ambiguities.

We present a first usage of Bokeh alignment on FACT, a 4m IACT on Canary island La Palma, Spain and further development of the method on the CTA MST prototype in Brelin Adlershof.

9908-176, Session PS3

Normalized and asynchronous mirror alignment for Cherenkov telescopes

Sebastian Achim Mueller, ETH Zürich (Switzerland)

Segmented reflectors are a great choice for Imaging Atmospheric Cherenkov Telescopes (IACTs). They are light weight and inexpensive due to mass production. Huge and fast apertures of segmented reflectors provide good image quality to recognize the few gamma ray air showers in the vast majority of cosmic ray showers.

However, the alignment of the individual mirror facets of a segmented reflector remains a challenge. We present a robust star tracking alignment method which is not restricted to perfectly clear nights and scales excellently with large numbers of facets. We call it NAMOD because it records asynchronous of the drive and normalizes the facet reflection responses to do the mirror orientation determination. NAMOD adopts the ideas of the VERITAS raster scan method but enhances it with an additional camera to become more flexible and robust.

While the telescope is wobbling close by a star, a reflector camera records the reflections in the mirror facets seen from the reflectors focal point. In addition a star camera is mounted parallel to the reflectors optical axis and records the sky seen by the telescope. The relative pointing direction of the telescope, with respect to the star, is calculated using the star camera image. Further, the star light reflections seen in the reflector camera images are normalized using the star light found in the star camera image. Both cameras are radiometrically calibrated, the star camera also is geometrically calibrated. For arbitrary wobble positions, the relative telescope pointing and the normalized mirror facet responses are recorded. From these records, the individual facet point spread functions and the facet orientations are reconstructed.

Since the normalized mirror facet responses are independent of the reference star, records on different reference stars can be combined what makes NAMOD more flexible. Further, partially cloud coverage is taken into account, too. When the reference star signal becomes too dim, recording is paused automatically.

As NAMOD records asynchronous of the drive, there is no communication between the drive and NAMOD which makes the method easy to install.

NAMOD does not need mirror facet actuation to determine the facet orientations, but it can create alignment instructions for the actuators. The full alignment state of the segmented reflector can be recorded without touching a single facet which is handy to feed the Monte Carlo simulations the current reflector state.

We present the Mini FACT test bench which was used to develop NAMOD to minimize the overlap with gamma ray observation time. We present the alignment results on FACT, a 4m IACT on Canary island La Palma, Spain. In addition, we compare NAMOD's alignment power to the optimum found in ray tracing simulations and present individual mirror facet point spread reconstructions.

9908-177, Session PS3

First results and future plans of the Canarias Infrared Camera Experiment (CIRCE) for the Gran Telescopio Canarias

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CIRCE is a near-infrared (1-2.5 micron) imager (upgrading to low-resolution spectrograph and polarimeter in Spring 2016) in operation as a visitor instrument on the Gran Telescopio Canarias 10.-4m telescope. It was built largely by graduate students and postdocs, with help from the UF Astronomy engineering group, and is funded by the University of Florida and the U.S. National Science Foundation. CIRCE is helping to fill the gap in time between GTC first light and the arrival of EMIR, and will also provide the following scientific capabilities to compliment EMIR after its arrival: high-resolution imaging, narrowband imaging, high-time-resolution

photometry, imaging- and spectro-polarimetry, and low-resolution spectroscopy. In this poster we present the first light and commissioning results for CIRCE, as well as review its current and future capabilities.

9908-178, Session PS3

Development of the NASA MCAT auxiliary telescope for orbital debris research

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The National Aeronautical and Space Administration (NASA) has recently deployed the Meter Class Autonomous Telescope (MCAT) to Ascension Island. MCAT will provide NASA with a dedicated optical sensor for observations of orbital debris with the goal of statistically sampling the orbital and photometric characteristics of the population from low Earth to Geosynchronous orbits. Additionally, a small auxiliary telescope, co-located with MCAT, is being deployed to augment its observations by providing near-simultaneous photometry and astrometry, as well as offloading low priority targets from MCAT's observing queue. It will also serve to provide an independent measurement of the seeing conditions to help monitor the quality of the data being produced by the larger telescope.

Comprised of off-the-shelf-components, the MCAT Auxiliary Telescope will have a 16-inch optical tube assembly, Sloan g'r'i'z' and Johnson/Cousins BVRI filters, and a fast tracking mount to help facilitate the tracking of objects in low Earth orbit. Tracking modes and tasking will be similar to MCAT except an emphasis will be placed on observations that provide more accurate initial orbit determination for the objects detected by MCAT. The near-simultaneous observations will also provide the opportunity for multi-filter color information of the debris objects to be obtained. Color information can further distinguish the individual objects within the population and provide insight into the reflectance properties of their surface material. The specific hardware, software, and tasking methodology of the MCAT Auxiliary Telescope is presented here.

9908-179, Session PS3

High-resolution camera system for very precisely measuring meteor velocities

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For the determination of meteor orbits in our solar system, trajectories are required of meteor trails inside our atmosphere, together with an estimate of the velocity. The velocity is traditionally measured with a rotating shutter in front of the lens or in between lens and film or detector. The accuracy of this modulation, as well as the modulation speed and astrometric accuracy of the exposure determine how well the velocity of the meteor can be estimated.

An alternative method for modulation is proposed, which does not rely on rotating choppers but instead on a Liquid Crystal (LC) optical shutter, which periodically switches between dark state and transparent, which was with success first applied to a meteor all-sky camera. Recent developments of this technology have now made available even faster LCs, which allows for modulation frequencies in the 100Hz – 1kHz range. This opens the way to observations with higher resolution, which should enable determination of orbits with higher accuracy, which is of large importance as the velocity parameter is the most sensitive parameter in determination of the orbit. Obtaining orbits with higher accuracy is highly interesting as it allows detection of fine structure in meteoroid streams at a more detailed level.

This paper, i) describes the details of high-resolution camera based on the LC shutter technology, ii) presents the first results obtained with this system, iii) discusses them and iv) discussed improvements for an even higher resolution system.

9908-180, Session PS3

CYRA: a cryogenic infrared spectrograph for the 1.6 meter new solar telescope at Big Bear Solar Observatory

Wenda Cao, Big Bear Solar Observatory (United States); Matt Penn, National Solar Observatory (United States); Claude Plymate, Nicolas Gorceix, Roy Coulter, Philip R. Goode, Big Bear Solar Observatory (United States)

CYRA (CrYogenic solar spectrogRAph) is a facility instrument of the 1.6 meter New Solar Telescope (NST) at the Big Bear Solar Observatory (BBSO), which is the highest resolution solar telescope in the U.S. in a generation. CYRA focuses on the study the near-infrared solar spectrum between 1 and 5 microns, an unexplored region which is not only fertile ground for photospheric magnetic diagnostics, but also allows a unique window into the chromosphere lying atop the photosphere. CYRA is the first fully cryogenic spectrograph in any solar observatory with its two predecessors, on the McMath-Pierce and Mees Telescopes, being based on warm optics except for the detectors and order sorting filters. CYRA is used to probe magnetic fields in various solar features and the quiet photosphere. CYRA measurements will allow new and better 3D extrapolations of the solar magnetic field and will provide more accurate boundary conditions for solar activity models. Superior spectral resolution of 150,000 and better allows enhanced observations of the chromosphere in the carbon monoxide (CO) spectral bands and will yield a better understanding of energy transport in the solar atmosphere. The CYRA instrument is divided into of two optical sub-systems: the Fore-Optics Module and the Spectrograph. The Spectrograph is the heart of the instrument and contains the IR detector, grating, slits, filters, and imaging optics all in a cryogenically cooled dewar (cryostat). The detector is based on a 2048 by 2048 pixels HAWAII 2 array produced by Teledyne Scientific & Imaging, LLC. The interior of the cryostat and the readout electronics are maintained at 70 Kelvin by helium refrigerant based cryo-coolers, while the IR array is cooled to 30 Kelvin. The Fore-Optics Module stabilizes the solar image, provides scanning capabilities, and transfers the light to the Spectrograph. CYRA has been installed and is undergoing its commissioning phase. This paper reports on the design and the implementation of CYRA in detail. First light scientific observations are presented and discussed.

9908-181, Session PS3

TAUKAM: a new prime-focus camera for the Tautenburg Schmidt Telescope

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The Thueringer Landessterwarte Tautenburg is upgrading the prime focus camera of the 2-m telescope. In its Schmidt configuration with the 1.34-m correction plate mounted, it is still the world's largest imaging Schmidt system. While the full CCD coverage of the 3.3 x 3.3 square degree field of view is prohibitive, the new 6k x 6k camera will provide an almost fourfold gain in field coverage (80' x 80' vs. 42' x 42') over that provided by the 2k

x 2k CDD currently still in use. A contract was signed with Photon Lines SAS for the delivery of a Spectral Instruments 1110S camera in 2017. The camera will be equipped with an e2v CCD PN 231-C6-1-G11 detector. The pixel size of 15 microns corresponds to 0.77 arcsec which is tailored to the seeing conditions (median 2 arcsec) at our site. The detector will be of deep-depletion type sporting an astro-multi-2 anti-reflection coating. The cooling will be provided by a closed-cycle cooler. Extra long cooling lines will permit to place the closed-cycle cooler into the basement, thus avoiding heat circulation in the dome. This, however, requires special suspension of the cooling lines to allow for the telescope movement. With the new camera we will move from Johnson-Cousins to SDSS filters, accompanied by a selection of special filters, e.g. narrow-band Halpha and [SII]. Due to the increased size of the filters (120 mm square) housing in a filter wheel is no longer possible because it would obstruct too much light in the tube. Instead, a robotic device will be used to grab a filter from a storage in the corner of the tube (which has a square cross-section), and move it into the optical path. The camera shutter of compact type will be delivered by Bonn Shutter. First light is foreseen in autumn 2017. Prime science objectives which will profit from the enhanced imaging capabilities are monitoring of potentially hazardous asteroids, variability of young stars and brown dwarfs, long-term variability of quasars, and gamma-ray burst afterglows. The project is funded by the federal state of Thuringia within the framework of infrastructure development.

9908-182, Session PS3

Calibrating the SN factory Integral Field Spectrograph (SNIFS) with SCALA

Daniel Küsters, Simona Lombardo, Marek Kowalski, Jakob Nordin, Mickael Rigault, Humboldt-Univ. zu Berlin (Germany); Greg Aldering, Univ. of California, Berkeley (United States) and Lawrence Berkeley National Lab. (United States)

We present upgrades and preliminary results of SCALA - a calibration device for the Supernova Integral Field Spectrograph (SNIFS). SCALA illuminates the University of Hawaii 2.2 m (UH88) telescope and monitors the emitted light with calibrated photodiodes. A monochromator is used as a tunable bandpass for a white light source, after which the light is fed through a fiber bundle towards six integrating spheres which illuminate 18 openings homogeneously. These homogeneously illuminated surfaces are projected onto the focal plane of the telescope, effectively creating an artificial planet with a constant surface brightness. This setup produces a flat field for the telescope which can be tuned in wavelength and calibrated with the photodiodes.

In Spring 2015 we performed calibrations together with spectrophotometric observations of standard stars.

The setup was improved with respect to the one described in Lombardo S. et al 2014, by the installation of an entrace pupil mask. The mask corrects for spatial throughput variations in the entrance pupil of the telescope and for systematic differences in flatfields, which are produced by SCALA. We will present preliminary throughput measurements of the system consisting of telescope and SNIFS.

One source of systematics is the influence of the calibration device on stray light and ghosts. In Spring 2015 we used different beam properties of SCALA to examine its influence on stray light. In the photometric observations we used the filters U, G, R, I, Z to sample the wavelength dependency. The observations do not show ghosts but have dust grain imprints. Ratios images of the different beam configurations show smooth variations across the field of view, which do not depend on the selected filter. The change in stray light is driven by the size of the artificial planet, and is only slightly influenced by the shape of the entrance pupil.

The mask will allow us to decrease the collecting area of the UH88 telescope by a factor of 10, effectively allowing for observations of brighter stars. In combination with closing some of the holes in the mask it will be possible to observe Vega or Sirius with the same instrument as used for supernovae.

9908-183, Session PS3

Visible Imaging Spectrometer (VIS) of the New Solar Telescope at Big Bear Solar Observatory

Wenda Cao, Nicolas Gorceix, Sergey Shumko, Philip R. Goode, Big Bear Solar Observatory (United States)

The Visible Imaging Spectrometer (VIS) has been developed and outfitted to the largest solar telescope, the 1.6-m New Solar Telescope (NST) at Big Bear Solar Observatory (BBSO). VIS is based on a single Fabry-Pérot Interferometer and interference filters to provide high resolution spectroscopic observation over a field-of-view of 74” by 64” in the visible wavelength range from 550 nm to 700 nm. With the aid of the BBSO adaptive optics (AO) system, the spatial resolution is close to the diffraction limit of the NST. The spectroscopic cadence reaches 10 seconds with a multi-frame sampling at each wavelength over the spectral lines. Currently available spectral lines include Ha (656.3 nm) and Na I D2 line (589 nm). This paper reports on the design, implementation, calibration and operation of VIS in detail. First light scientific observations are presented and discussed.

9908-185, Session PS3

JPCam: development of a 1.2 g-pixel camera for the J-PAS survey

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JPCam is a 14-CCD mosaic camera, using the new e2v 9k-by-9k 10 m-pixel, 16-channel detectors to be deployed on a dedicated 2.55 m wide-field telescope at the OAJ (Observatorio Astrofísico de Javalambre) in Aragon, Spain. The camera is designed to perform a Baryon Acoustic Oscillations (BAO) survey of the northern sky. The J-PAS survey strategy will use 54 relatively narrow-band (13.8 nm) filters equi-spaced between 370 and 920 nm plus 3 broad-band filters to achieve unprecedented photometric red-shift accuracies for faint galaxies over 8000 square degrees of sky. This paper presents an overview of JPCam as well as a brief outline of the main J-PAS project.

9908-186, Session PS3

Design and development of control unit and software for the ADFOSC instrument of the 3.6 m Devasthal optical telescope

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In this paper, we describe the details of inhouse developed control unit and GUI software for positioning two filter wheels, a slit wheel and a grism wheel of the ARIES Devasthal faint object spectrograph camera (ADFOSC) instrument. This ADFOSC instrument is a first generation instrument being built for the 3.6 m Devasthal optical telescope (DOT). The control hardware consists of five electronic boards based on low cost 8-bit PIC microcontrollers and are distributed over I2C bus. The four wheels are controlled by four identical boards which are configured in I2C slave mode while the fifth board acts as an I2C master and sends and receives commands with the slave boards. The master also communicates with the interfacing PC over TCP/IP protocol using simple ASCII commands. For

moving the wheels stepper motors along with suitable amplifiers have been employed and homing

is achieved using hall effect sensors. By implementing distributed control units having identical design modularity is achieved enabling easier maintenance and upgradation. A GUI based software for commanding the instrument is developed in Microsoft Visual C++. For operating the system during observations a user selects normal mode while during maintenance engineering mode is used. A detailed time-stamped log of commands and operation is continuously generated. Both the control unit and the software have been successfully tested and integrated with the ADFOSC instrument.

9908-187, Session PS3

The opto-mechanical design for GMOX: a next-generation instrument concept for Gemini

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We present the opto-mechanical design of GMOX, the Gemini Multi-Object eXtra-wide-band spectrograph, a potential next-generation (Gen-4 #3) facility-class instrument for Gemini. GMOX is a wide-band, multi-object, spectrograph with spectral coverage spanning 350 nm to 2.4 um with a nominal resolving power of R~5000. Through the use of Digital Micromirror Device (DMD) technology, GMOX will be able to acquire spectra from hundreds of sources simultaneously, offering unparalleled flexibility in target selection. Utilizing this technology, GMOX can rapidly adapt individual slits to either seeing-limited or diffraction-limited conditions. The optical design splits the bandpass into three arms, blue, red, and near infrared, with the near-infrared arm being split into three channels covering the Y+J band, H band, and K band. A slit viewing camera in each arm provides imaging capability for target acquisition and fast-feedback for adaptive optics control with either ALTAIR (Gemini North) or GeMS (Gemini South). Mounted at the Cassegrain focus, GMOX is a large (1.3 m x 2.8 m x 2.0 m) complex instrument, with six dichroics, three DMDs (one per arm), five science cameras, and three acquisition cameras. Roughly half of these optics, including one DMD, operate at cryogenic temperature. To maximize stiffness and simplify assembly and alignment, the opto-mechanics are divided into three main sub-assemblies, including a near-infrared cryostat, each having sub-benches to facilitate ease of alignment and testing of the optics. In this paper we present the conceptual opto-mechanical design of GMOX, with an emphasis on the mounting strategy for the optics and the DMDs, as well as thermal design details related to the near-infrared cryostat.

9908-188, Session PS3

Photonic Lightbuckets for astronomical optical spectrographs

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In order to achieve low-cost large-aperture ground-based optical spectroscopy systems, we are using inexpensive commercial-off-the-shelf (COTS) telescopes and components (such as acquisition/guide CCDs and control computers) together with innovative 3D printed components to create semi-autonomous small telescope arrays and fiber-fed spectrographs. Small telescopes used conjointly ("photonic lightbuckets") and connected by our new fiber-optic linkage have the effective light-gathering area of a larger telescope for about one-tenth of the cost. We are currently putting together a four-telescope version of the instrument to be used with the bHROS spectrograph in San Juan, Argentina. Target applications for photonic lightbuckets include compact object mass measurements, LSST follow up, LIGO/LISA electromagnetic counterpart follow up to gravitational wave observations, exoplanet atmosphere measurements, and cosmological acceleration measurements.

9908-189, Session PS3

The AST3-NIR camera for the Kunlun Infrared Sky Survey

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AST3-NIR is a new infrared camera for deployment with the AST3-3 wide-field Schmidt telescope to Dome A on the Antarctic plateau. This project is designed to take advantage of the low Antarctic infrared sky thermal background (particularly within the 'Kdark' near infrared atmospheric window at 2.4 micron) and the long Antarctic nights to provide high sensitivity temporal data from astronomical sources. AST3-NIR is a funded project, currently in the preliminary design phase, that is due for deployment in early 2017. The facility will be used to conduct the Kunlun Infrared Sky Survey (KISS), with science goals addressing research across a range of galactic and extragalactic areas.

The baseline instrument concept consists of a 2.5 micron cut-off HgCdTe detector array, mounted in a cryostat with relay optics, Kdark filter, internal baffling, a cold stop, and a focus drive. The optical relay provides a focal-plane plate-scale that is optimised for high-sensitivity wide-field observations given the expected seeing conditions, the telescope diffraction limit, and the lens fabrication and alignment tolerances. The Kdark filter bandwidth and centre wavelength is designed to maximise sensitivity for the expected atmospheric thermal emission spectrum and the telescope thermal emission properties. The cryostat design is driven towards reliability and simplicity by the extreme environmental conditions and the requirement for remote operation with only a yearly service interval.

The AST3-NIR camera mounts to a flange on the AST3-3 telescope at the Newtonian focus. The telescope optical prescription is identical to the first two AST3 telescopes, which were designed for wide field of view optical application. The telescope is a modified Schmidt type with a 0.5 m plano-aspheric corrector plate followed by a 0.68 m ellipsoid primary mirror with a flat folding secondary mirror. The telescope tube is enclosed and the corrector window has an indium-tin-oxide coating to avoid frost formation. The telescope and instrument include a control system that interfaces to a remote PLATO system for power generation, communications and control.

The Kunlun Infrared Sky Survey's uniqueness is in detection of changes in luminosity of astronomical sources in the infrared. This leads to a range of science goals that includes the physics of active galactic nuclei,

supernovae and gamma ray bursters, the terminal phases of red giants and initial phases of protostars, the discovery of exoplanets, and the level of the cosmic infrared background and its angular fluctuations.

9908-190, Session PS3

The optical design of GMOX: a next-generation instrument concept for Gemini

Robert H. Barkhouser, Johns Hopkins Univ. (United States); Massimo Robberto, Johns Hopkins Univ. (United States) and Space Telescope Science Institute (United States); Stephen A. Smee, Johns Hopkins Univ. (United States); Zoran Ninkov, Rochester Institute of Technology (United States); Mario Gennaro, Space Telescope Science Institute (United States); Timothy M. Heckman, Johns Hopkins Univ. (United States)

We present the optical design of GMOX, the Gemini Multi-Object eXtra-wide-band spectrograph. GMOX was selected as part of the Gemini Instrument Feasibility Study to develop capabilities and requirements for the next facility instrument (Gen4#3) for the observatory. We envision GMOX covering the entire optical/near-IR wavelength range accessible from the ground, from 3500 Å in the U-band up to 2.4 μm in the K-band, with nominal resolving power R~5000. To maximize efficiency the bandpass is split into three spectrograph arms – blue, red, and near-infrared – with the near-infrared arm further split into three channels covering the Y+J, H, and K bands. At the heart of each arm is a Digital Micromirror Device (DMD) serving as a programmable slit array. This technology will enable GMOX to simultaneously acquire hundreds of spectra of faint sources in crowded fields with unparalleled spatial resolution, optimally adapting to both seeing-limited and diffraction-limited conditions provided by ALTAIR and GeMS at Gemini North and South, respectively. Fed by GeMS at f/33, GMOX can synthesize slits as small as 40 mas (corresponding to a single HST/WFC3 CCD pixel) over its entire 85 x 45 arcsec field of view. With either ALTAIR or the native telescope focal ratio of f/16, both the slit and field size double. In this paper we discuss the conceptual optical design of GMOX including, for each arm, the pre-slit optics, DMD slit array, off-axis Schmidt collimator, VPH grating, and refractive spectrograph and slit-viewing cameras.

9908-191, Session PS3

Intelligent camera SiPM for astrophysical applications

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World scale projects dedicated to ground based astronomy require new technology developments in many fields and also for realization of compact focal plane cameras. Usually these cameras are dedicated to specific astrophysical applications and optimized for a particular telescope configuration. However in many cases single telescopes (as well as arrays) can be well suited for scientific studies that were not driving the requirements in the project-planning phase. The objective of this work is an assessment towards the development of an Intelligent Camera SiPM (IC-SiPM) for astrophysical applications, based on silicon multiplier (SiPM) and programmable electronics (FPGA). IC-SiPM should be easily adaptable to different plate scale of currently existing or under construction telescopes for big science projects. The flexibility will be guaranteed by multi-size SiPM arrays, multi-function channels conditioning electronics, auto-focus and centring electro-mechanical system based on FPGA.

9908-192, Session PS3

Blue camera of the Keck cosmic web imager, fabrication and testing

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The Keck Cosmic Web Imager (KCWI) is a new facility instrument currently being completed for the Keck II Telescope at the W. M. Keck Observatory. The blue camera for KCWI uses nine all spherical lens elements (including a field flattener as the vacuum window to the CCD dewar). The mounts of all lenses are elastomeric and are required to hold the lens to better than 0.001 inches placement accuracy at the normal operating temperature of 0C without exerting sufficient force to distort the them. The camera was assembled at 21C using a precession turntable, precision micrometers, and height gages, and shims. We achieved an overall placement accuracy within 0.001 inches for the camera, measured mechanically. The optical performance was predicted for 21C and we tested the camera by both finding the back focal distance, and with our Zygo Interferometer. We also cold cycled the camera in our cold chamber. The camera is currently mounted in the KCWI instrument as it is being integrated and tested at the California Institute of Technology in Pasadena, CA.

9908-193, Session PS3

HARDWARE.astronomy: an open-source hardware initiative for astronomy

Carl Ferkinhoff, Winona State Univ. (United States)

The .astronomy conference series, now completing its 8th event, has been successful in bringing together astronomers to develop open-source web tools and software to support research, education and outreach. Meanwhile, outside of astronomy the open design movement has driven a revolution of affordable electronic and electromechanical devices (e.g. Arduino, RaspberryPi) that are easily developed by product developers and consumers alike. An “Open Source Hardware” definition, similar to that for open-source hardware, has enabled this revolution. A key characteristic of these open devices is that their design, firmware & software files a readily published online via open-source licences. Here we introduce a new initiative—HARDWARE.astronomy—that will support open-source hardware the development of astronomical instrumentation. In this paper will discuss the goals of this project to: 1) develop low cost devices for astronomical observations and develop astronomical instruments based on open-hardware devices and principles; 2) make all hardware, software and firmware immediately available to the broader community per the open-source principle; 3) invest undergraduates in the development of astronomical instruments; and lastly 4) develop principles of open hardware for the astronomical community that will enable other researchers to publish their projects through the initiative. In discussing these goals we will briefly introduce two intial open-source projects, a robotic observatory and thermomtry system—The ROBh.aT Network and H.aHK Box, respectively.

9908-194, Session PS3

ha.HK box: the HARDWARE.astronomy housekeeping box

Carl Ferkinhoff, Winona State Univ. (United States)

While often unglamourous yet critical part of most astronomical instruments is cryogenic temperature monitoring and control. Depending on the operating wavelength of the instrument this could mean stable temperatures at 40 to 70 Kelvin or maintaining 100 mK at sub-microKelvin stability as for many submillimeter bolometer systems. Here we describe a project of the HARDWARE.astronomy initiative to build a low-cost open-source temperature monitoring and control system. The HARDWARE. astronomy Housekeeping Box, or ha.HK Box (prounouced "hack") is developed primarily by undergraduates and employs existing open-source devices (e.g Arduino, RaspberryPi) to reduce costs while also limiting the complexity of the development. The ha.HK Box features a base system with a control computer and 10 expansion slots that can be filled with a variety of expansion cards. These cards include AC and DC excited 4-wire bridges, 2-wire bridge, and PID controller card. The base-system will also be able to interface with a to-be-designed motor-control system and other devices over serial port and ethernet. The first deployment of the ha.HK Box will be for the ZEUS-2 submillimeter grating spectrometer though all design, firmware, software and parts list will be published online allowing for other projects to adopt the system and creat custom expansion cards as needed.

9908-195, Session PS3

Colored exosolar atmospheres: a novel approach

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The exoplanet revolution is well underway. The last decade has seen order-of-magnitude increases in the number of known planets beyond the Solar system.

Detailed characterization of exoplanetary atmospheres provide the best means for distinguishing the makeup of their outer layers, and the only hope for understanding the interplay between initial composition chemistry, dynamics & circulation, and disequilibrium processes.

While pioneering work on the observational side has produced the first important detections of atmospheric molecules for the class of transiting exoplanets, important limitations are still present due to the lack of systematic, repeated measurements with optimized instrumentation at both visible (VIS) and near-infrared (NIR) wavelengths. It is thus of fundamental importance to explore quantitatively possible avenues for improvements. In this paper we report initial results of a feasibility study for the prototype of a versatile multi-band imaging system for very high-precision differential photometry that exploits the choice of specifically selected narrow-band filters and novel ideas for the execution of simultaneous VIS & NIR measurements.

Starting from the fundamental system requirements driven by the science case at hand, we describe a set of three opto-mechanical solutions for the instrument prototype: 1) a radial distribution of the optical flux using dichroic filters for the wavelength separation and narrow-band filters or liquid crystal filters for the observations; 2) a tree distribution of the optical flux (implying 2 separate foci), with the same technique used for the beam separation and filtering; 3) an 'exotic' solution consisting of the study of a complete optical system (i.e. a brand new telescope) that exploits the chromaticity errors of a reflecting surface for directing the different wavelengths at different foci.

In this paper we present the first results of the study phase for the three solutions, as well as the results of two laboratory prototypes (related to the first two options), that simulate the most critical aspects of the future instrument.

9908-196, Session PS3

ROBH.aT network: the robotic observatory by HARDWARE.astronomy and telescope network

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There are over 4,500 institutions of higher education in the United States, of those over 1,800 are Bachelor degree granting institution (2010 Carnegie Classification; National Center for Educations Statistics, IPEDS Fall Enrollment (2009)). Even if only 1 in 10 has a campus observatory, that is still nearly 200 small telescopes spread across the country. While certainly the sites are less than ideal and many campus telescopes will be small, ~30 - 40 cm in diameter, this number of telescopes is still significant and could be especially useful for transient studies in the LSST era. The educational and outreach impact of having robotic observatories at educational institutions is also profound. Realizing the potential of all theses telescopes requires automating and connecting these observatories into a network. The Robotic Observatory by HARDWARE.astronomy and Telescope Network, or ROBH.aT Network (pronounced "robot") aims to do just this by leveraging open-source hardware devices to develop the hardware necessary to robotize a telescope at low-cost and with primarily undergraduate students. Future phases of the project will deploy a task-scheduler for automated observing locally and integrating all telescopes into a large heterogenous-network. Here we report of the initial work in automating the observatory at Winona State University.

9908-197, Session PS3

Concepts of the mosaic array of numerous ultra-small lens (MANUL) design

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The lack precise and accurate time series photometry for very bright (V<=6) stars implies the development of instrumentation capable to perform continuous imaging of these objects. In addition, the advancement of embedded electronics makes feasible to build small-scale highly integrated and dedicated electronics. In this presentation we introduce the main concepts, early prototyping and photometric results of the Mosaic Array of Numerous Ultrasmall Lens (MANUL) system, a palm-sized ``single-board astronomical observatory'' designed for permanent low-resolution, multi-color photometric measurements of the brightest stars -- from Sirius down to the faint limit of V=6-7 magnitudes.

The MANUL system is a configurable setup of small-footprint stacked printed circuit boards, having a diameter of 5 centimeters, on which all of the necessary parts and optical elements are mounted. The circuit boards support the CMOS imaging sensors (up to three), the filters and the lens, the core data acquisition control electronics which are based on an ARM

Cortex-M4 MCU, a TCP/IP and Ethernet interface and various auxiliary parts (e.g. power subsystem, clocking, alternate low-bandwidth control). The MCU itself is powerful enough to perform readout and downlink of the three 5 megapixel CMOS sensors within a second in a round-robin fashion while the sensors are continuously operating in electronic rolling shutter mode. MANUL units can then be combined regarding to the actual needs. For instance, a single-module setup combined with fish-eye optics (e.g. f=2.2mm, f/2.5 lens) can used as an all-sky camera. With larger focal lengths, e.g. with f=6.5mm, f/1.6 lens, a sensor with 2.2 micron pixels has an imaging resolution of 1.2 arcminutes per pixel and seven of such units is capable to cover the visible sky above 30 degrees of horizontal altitude.

As we present here, initial prototyping of the system shows that using a gross of 3 minutes long exposure time (i.e. the combination of 9 rolling shutter frames, 20 seconds of each), one can achieve a signal-to-noise ratio with an average of 4-6 for V=6 stars. In addition, the linearity of the CMOS sensor is also validated within 1.2-sigma by considering 200 stars in the brightness regime of V=0...6 appearing above 50 degrees of horizontal altitude.

Although the the optical setup seems rather simple compared to conventional telescopes, a 7-unit mosaic setup of three-sensor MANUL modules provide an integral etendue of 0.5 deg^2 m^2. Due to the small footprint, the quick development cycle, the lack of moving parts and the low cost, network operations of multi-module MANUL cameras are also feasible. The MANUL design is complementary to the scientific domains of Fly's Eye (or similar) initiatives. It also covers the same regime targeted by Mascara but on a definitely smaller scale and the inclusion of color information. It is therefore an interesting experimental technology for very cheap and complementary astrophysics.

9908-198, Session PS3

DKIST visible broadband imager alignment in laboratory: first results

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The Visible Broadband Imager (VBI) Blue and Red channels are the first Daniel K. Inouye Solar Telescope (DKIST) instruments that have been aligned and tested in a laboratory. This paper describes the optical alignment method of the VBI as performed in the laboratory. The objective of this preliminary alignment is to test and validate the optical alignment method that will be used during final alignment on the telescope, to measure the VBI performances and to verify that it meets specification. The optical alignment method is defined by three major steps. The first step is realized by combining the optical and mechanical models into the Spatial Analyzer® (SA) software, and extracting the data serving as target values during alignment. The second step is the mechanical alignment and allows to accurately position the optics in the instrument coordinate system by using a Coordinate Measurement Machine (CMM) arm and a theodolite. This step has led to a great initial positioning and has allowed reaching an initial wavefront error before optical alignment close to the specification. The last step, performed by interferometry, allows fine alignment to compensate the residual aberrations created by misalignment and manufacturing tolerances. This paper presents also an alignment method to compute the shifts and tilts of compensating lenses to correct the residual aberrations. This paper describes first results of the VBI instruments performances measured in the laboratory and confirm the validity of the alignment process that will be reproduced during final alignment on the telescope.

9908-199, Session PS3

Nanoradian ground-based astrometry, optical navigation, and artificial reference stars

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Deep space optical communications will significantly increase data rate over traditional radio frequency communications.

Spacecraft carrying optical communication lasers can be treated artificial stars from an astrometric perspective, which in turn may enable navigation from optically-determined metrics.

ESA's Gaia mission, currently in operation, is surveying a billion stars down to 20th magnitude providing catalog with better than 100 micro arcsecond astrometry at the end of the mission.

Relative astrometry of spacecraft with respect to Gaia reference stars then provides spacecraft positions in the plane-of-sky, forming 3-d positions for optical navigation when combined with optical ranging data.

To be sufficient for navigation, we need to achieve nanoradian accuracy in absolute astrometry, which is comparable to the current Deep Space Network delta-Differential One-way Ranging measurements.

In this paper, we describe our error budget and techniques for achieving nanoradian level ground-base astrometry.

The key to success is to perform very narrow angle astrometry (with angular separation < 20 arcsec) using the abundant Gaia reference stars and to accurately calibrate systematic errors like field distortion, differential atmospheric refraction effects, and detector responses.

In addition, it is crucial to use the synthetic tracking technique for high precision astrometry of a moving object. Synthetic tracking is a technique that we developed for detecting fast moving asteroids by taking multiple short exposure images to replace long exposure images to avoid streaked images, which degrades signal-to-noise ratio and introduces non-common mode atmospheric effect into narrow angle relative astrometry of moving objects. Preliminary results from the Pomona College's 1 meter telescope at Table Mountain Observatory will be presented. We also discuss how these spacecrafts may serve as artificial reference stars for precise astrometry to detect exoplanets and to supply additional measurements for tying the International Celestial Reference Frame with the Gaia reference frame.

9908-200, Session PS3

Characterization of commercial photographic camera lenses for use in astronomical instrumentation

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We present measurements of the spectral response function, absolute throughput, and image quality of a sample of commercially available photographic camera lenses. We also investigate the response of the lenses at a range of f-ratio and focal length settings. We show that the lenses have > 50% throughput over 400 < ? < 700 nm and acceptable image quality over a relatively large field of view. We conclude that commercially available lenses are a viable and cost-effective alternative to custom-built optical systems in select astronomical applications.

9908-201, Session PS3

Okayama astrophysical observatory wide-field camera: status and performance

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We present the design, current status and performance of our wide field near infrared camera, OAOWFC, developed at Okayama Astrophysical Observatory, NAOJ. OAOWFC is a near-infrared wide-area imager whose aperture is 0.91m. It works in Y, J, H and Ks bands and the field of view is 0.47 x 0.47 square degrees, which is realized by a HAWAII PACE detector of 1K x 1K pixels. It will be used to survey the Galactic plane for variability and search for transients such as GRBs or optical counterpart of gravitational wave sources. In this paper, we will present the status and performance.

OAOWFC was constructed as a renewal of existing 0.91m telescope manufactured in 1959. Almost all the parts of the telescope are used in the new camera, except for the top-ring and the secondary mirror. We followed the optical design of UKIRT WFCAM and finally realized a field of view of 1.3 degrees or 52mm in diameter. The optics is composed by forward Cassegrain and quasi Schmidt. Once the forward Cassegrain makes an image after secondary mirror, it is relayed by a field lens, and re-imaged by quasi Schmidt. A clear pupil is formed just after the collimator in the quasi Schmidt, so we placed the whole quasi Schmidt optics into a dedicated cryostat and cool them down below 130K for the purpose of enabling the deep K-band imaging. Our refrigerator has enough cooling power, the inside the cryostat is painted with infrared black to reduce stray light as possible. The cooling is accomplished within 24 hours. OAOWFC is mounted on fork-equatorial. The maximum slew speed of 2 deg. /sec enables to point any direction in the sky within 2 minutes. The pointing accuracy is 5 arcsec RMS enough small compared with the wideness of the image area.

We have carried out a mini survey to search for variability in the Galactic plane and got successful results. The survey was made as a part of performance verification. The survey area, 6 square degrees toward Scutum-Centaurus arm, was selected in two aspects. From the astronomical point of view, it is expected that there are many variable stars left undiscovered. From the technical point of view, the area is the toughest region to make an accurate photometry, since the area is highest in number density. If we succeed in photometry with enough accuracy, the reduction method can be applied to any other region in the sky. The survey was made from April to August in 2015, and got about 40 epochs. The PSF fitting photometry with SExtractor and PSFEx was applied and the final photometric error of 2% was confirmed. We have discovered about 700 variable stars in the area and identified 300 long period variables such as Miras, 300 irregular variables and 30 Cepheid candidates. Consequently, we have succeeded to demonstrate that OAOWFC is a useful instrument to investigate the Galactic variability in the NIR.

9908-202, Session PS3

Efficient coupling of starlight into single mode photonics using Adaptive Injection (AI)

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By using single-mode fibres, single-mode interferometers and nullers stand to revolutionise ultra-high resolution, high contrast imaging, leading to direct imaging of Earth-like exoplanets. Single-mode spectrographs provide mitigation of modal noise and compact size.

However, the successful use of these technologies faces a major hurdle: the initial injection of starlight into single mode photonics is extremely difficult. Small mode-field diameter (typically less than ten microns) and restrictive NA means that directly injecting the seeing-limited telescope pupil into a single mode fibre is virtually impossible. An extreme adaptive optics system is one solution, but these extremely expensive and complex systems are beyond the reach of all but the major 8 m class telescopes.

Here we present an alternative solution - adaptive injection (AI). Analogous to adaptive optics (AO), this system actively adjusts the wavefront in real-time as it varies with the seeing. However rather than attempting to produce the flattest wavefront possible across the whole pupil, AI optimises the wavefront for the best possible injection into an array of single-mode waveguides or fibres. The telescope pupil is re-imaged onto a MEMS segmented deformable mirror, and thence onto a two-dimensional array of single mode waveguides (with matching microlens array (MLA)). The MEMS mirror segments are matched one-to-one with the single-mode waveguide and MLA, thus dividing the telescope pupil into an array of sub-pupils. The array is sized such that each sub-pupil is roughly the same size as the Fried parameter r0. Via a dichroic mirror, the pupil is also imaged into a separate matched MLA and camera to act as a wavefront sensor.

For single-mode injection, this system has an advantage over an AO system of comparable actuator count. By segmenting the telescope pupil into a series of subapertures with sizes of order r0, the problem of injecting the complex seeing-induced PSF is reduced to a number of simple, independent tip/tilt loops. Due to the extreme sensitivity of injection efficiency on the angle of the incident light, the optimum injection is not achieved with a flat wavefront; rather, the beam of each sub-aperture requires an offset applied as a tip/tilt term to the corresponding MEMS mirror segment (determined beforehand by way of a raster scan). Since each MEMS segment has independent tip/tilt control, the required offset for each waveguide becomes the appropriate zero-point for the AI loop. Adjacent segments can have entirely opposing tip/tilt values if necessary. A traditional membrane DM with the same actuator number would have just over 1 actuator per sub-pupil, and so independent tip/tilt control would not be possible. The remaining coupling losses are due to higher order structure within the sub-aperture, which has been found to be small. For interferometric applications, higher fringe visibilities can be obtained if the matched wavefront sensor is used in a Shack-Hartmann mode, and the appropriate piston terms are also applied to the segments.

In on-sky and laboratory tests, we have found that injection efficiency using the AI system is significantly higher than that using a conventional AO system of similar actuator count.

9908-203, Session PS3

High-resolution abundances distribution in disk galaxy with SITELLE

Laurie Rousseau-Nepton, Laurent Drissen, Carmelle Robert, Thomas Martin, Univ. Laval (Canada)

SITELLE is the new Imaging Fourier Transform Spectrograph (IFTS) of the

Canada-France-Hawaii Telescope (CFHT).

This IFTS can produce an impressive number of 4 million spectra in a single data cube. Its large contiguous spatial coverage (11'x11') and its high spatial resolution (0.32'' pixels and ~ 0.75'' average seeing) allow to study the ionized gas emission surrounding massive star (HII regions) with an unprecedented view. The commissioning and science verification runs revealed the incredible power of this instrument for the study of star formation in the extended disk of galaxies. This poster presents some of the first results obtained on the nearby spiral galaxy NGC628, including the detection of extended star formation using the H? and the [OII]?3727 tracers. Precise intensity and kinematic maps will be shown. With this data sample, we focused on the problematic of characterizing the ionized gas physical properties in thousands of HII regions detected in NGC628. Photoionization models are an essential tool to derive the physical properties of the ionized gas over the whole surface of the galaxy disk. A reliable gas abundance prediction from photoionization models requires strong constraints on the physical conditions of star-forming regions and multiple abundance sensitive line ratios.

A good knowledge of the gas abundances distributions in the galaxies' extended disk can lead to a better understanding of the role played by the different enrichment and mixing processes that modify the content of galaxies and drive their evolution. Within this context, observing and characterizing the star-forming regions located in the outskirts of galaxies is important and SITELLE is well suited for this task.

9908-204, Session PS3

Concept Design of an 80-dual polarization element Cryogenic Phased Array Camera for the Arecibo Radio Telescope

German Cortes-Medellin, Univ. de Antioquia (Colombia) and Cornell Univ. (United States); Stephen C. Parshley, Donald B. Campbell, Cornell Univ. (United States); Karl Warnick, Brian D. Jeffs, Brigham Young Univ. (United States)

Phased array antenna technology enables access to the instantaneous field of view (FoV) of large telescope optics, which combined with fully cryogenic array elements and amplifiers results in survey speed improvements of several orders of magnitude. The proposed Arecibo Observatory L-band cryogenic phased array camera (AO40) will enable faster and/or deeper surveys, with science objectives that include dark matter dominated mini-halos in our Galaxy, the detection of gravitational waves by using precision pulsar timing, and the emerging potential for discovery of the transient radio sky.

We have developed a full concept design of an 80 dual polarized element cryogenic phased array camera for the Arecibo radio telescope. The front-end camera will cover the frequency band from 1.280 GHz to 1.720 GHz. In the new camera design we have incorporated major changes in the vacuum window design, now 1360 mm in diameter, that improves the electromagnetic performance of the array. We have also made changes to the element array configuration that allows us to scale the cryo-mechanical design to 80 dual polarization elements by utilizing four-fold symmetry for the array.

The camera will be capable of producing 40 dual polarized real-time digitally formed beams with a system temperature goal of < 30K. The total bandwidth per channel is 312.5 MHz (tunable within the front-end frequency band), yielding an instantaneous processing bandwidth of 50 GHz. The back-end will provide 800 coarse channels with a bandwidth of 390.625 kHz and 26,600 fine channels with a resolution of 12.2 kHz.

We will present the results of the cryo-design modifications and final concept design of the cryo-PAF camera.

9908-205, Session PS3

The Harlan J. Smith Telescope direct imaging auxiliary functions instrument

Phillip J. MacQueen, Joseph L. Strubhar, Gordon L. Wesley, Peter Samuel Odoms, Robert D. Edmonston, The Univ. of Texas at Austin (United States)

DIAFI, the Direct Imaging Auxiliary Functions Instrument, is a GUI operated instrument used for CCD imaging through filters at the f/8.8 focus of the McDonald Observatory 2.7 m Harlan J. Smith Telescope. It has a maximum field of view of 8.8 arcminutes square, and a 300–1050 nm bandwidth. The functions provided by DIAFI in support of CCD imaging are mounting the CCD detector system to the telescope, a 40-filter filter changer for 76 .2 mm square filters, an image quality corrected offset guider with filters and independent focus control, a zero power dissipation shutter, a deployable frame transfer mask, and a neutral density filter that can be used in series with the science filters.

This paper serves as a reference for the instrument, giving characteristics and performance. It also details the novel engineering aspects of DIAFI. The filter carousel operates with varying gravity vector and temperature at the cassegrain focus, and is highly reliable as a function of mechanical design, detailed electronic interlocks, and diagnostics. The off axis guider includes a toroidal folding flat to achromatically correct the off-axis aberrations of the Ritchie Chretien telescope. The detector mount and guider optical path were quickly and accurately aligned to the mounting flange with a coordinate measuring machine.

9908-206, Session PS3

Astrophysical Research Consortium Telescope Imaging Camera (ARCTIC) facility optical imager for the Apache Point Observatory 3.5m Telescope

Joseph Huehnerhoff, Apache Point Observatory (United States) and Univ. of Washington (United States); William Ketzeback, Alaina Bradley, Jack Dembicky, Apache Point Observatory (United States); Caitlin Doughty, New Mexico State Univ. (United States); Suzanne Hawley, Courtney Johnson, Univ. of Washington (United States); Mark Klaene, Ed Leon, Russet McMillan, Apache Point Observatory (United States); Russell Owen, Conor Sayres, Tyler Sheen, Univ. of Washington (United States); Alysha Shugart, Apache Point Observatory (United States)

The Astrophysical Research Consortium Telescope Imaging Camera, ARCTIC, is a new optical imaging camera now in use at the ARC 3.5m telescope at Apache Point Observatory. As a facility instrument, the design criteria broadly encompassed many current and future science opportunities, and the components were built for quick repair or replacement, to minimize down-time. Examples include a quick change shutter, filter drive components accessible from the exterior and redundant amplifiers on the detector. The detector is a Semiconductor Technology Associates (STA) device with several key properties (e.g. high quantum efficiency, low read-noise, quick readout, minimal fringing, operational bandpass 350-950nm). Focal reducing optics (f/10.3 to f/8.0) were built to control aberrations over a 7.8'x7.8' field, with a plate scale of 0.11" per 15 micron pixel. The instrument body and dewar were designed to be simple and robust with only two components to the structure forward of the dewar, which in turn has minimal feedthroughs and permeation areas and holds a vacuum <10^-8 Torr. A custom shutter was also designed, using pneumatics as the driving force. This device provides exceptional performance and reduces heat near the optical path.

Measured performance is repeatable at the 2ms level and offers field uniformity to the same level of precision. The ARCTIC facility imager will provide excellent science capability with robust operation and minimal maintenance for the next decade or more at APO.

9908-207, Session PS3

Status of Focal Plane Instrumentation (FPI) project of the 4m DAG telescope

Onur Keskin, Isik Üniv. (Turkey); Sinan K. Yerli, Middle East Technical Univ. (Turkey); Cahit Yesilyaprak, Atatürk Üniv. (Turkey); Tolga Guver, Istanbul Univ. (Turkey)

DAG (Eastern Anatolia Observatory in Turkish) will be the newest and largest (4m) observatory of Turkey in both optical and near-infrared with its robust observing site infrastructure. The telescope is designed to house 2 Nasmyth platforms which will be dedicated to IR and VIS observations. In order to benefit both national and international science communities, DAG technical teams in collaboration with ISIK University (for Adaptive Optics Systems), Middle East Technical University (for test, measurement and calibration of DAG instruments), Istanbul University (for new kind of instrumentations, e.g. MKIDs), and Ataturk University (for IR & VIS detectors) formed a collaboration. In this paper the status updates from the co-owned FPI project will be presented along with possible collaboration opportunities.

9908-208, Session PS3

RIMAS: infrared imager-spectrometer for the Discovery Channel Telescope

Alexander S. Kutyrev, NASA Goddard Space Flight Ctr. (United States) and Univ. of Maryland, College Park (United States); Vicki L. Toy, John I. Capone, Univ. of Maryland, College Park (United States); Gennadiy N. Lotkin, Beacon Systems, Inc. (United States) and NASA Goddard Space Flight Ctr. (United States); Neil A. Gehrels, Samuel H. Moseley, NASA Goddard Space Flight Ctr. (United States); Sylvain Veilleux, Stuart N. Vogel, Univ. of Maryland, College Park (United States); Thomas Hams, Univ. of Maryland, College Park (United States) and NASA Goddard Space Flight Ctr. (United States); Frederick D. Robinson, Beacon Systems, Inc. (United States) and NASA Goddard Space Flight Ctr. (United States)

RIMAS is being built for a fast response to transient events detected by Swift high energy observatory. It will also become a general purpose instrument at the Discovery channel telescope. Two spectral arms arrangement with two separate H2RG 2048 x 2048 pixels detectors increases the efficiency of the instrument, allows for compact dosing and makes it possible to acquire the high resolution (R~5000) spectrum over the full spectral range form 950nm to 2350nm in one setting. The imaging mode with the 3 arcminutes (0.35" per pixel plate scale) field of view provide a large enough area for reliable identification and photometry of the transient afterglow candidate. For an accurate pointing and tracking of the telescope in the spectroscopy mode there is a slit viewing detector operating in J band. This viewer is sensitive enough to provide reliable positioning of the source for the full range of the sources brightnesses that can be observed spectroscopically with the instrument.

9908-209, Session PS3

HAWC+ facility far-infrared camera and polarimeter for SOFIA

Charles D. Dowell, Jet Propulsion Lab. (United States); Mandana Amiri, The Univ. of British Columbia (Canada); Dominic J. Benford, NASA Goddard Space Flight Ctr. (United States); Marc Berthoud, The Univ. of Chicago (United States); Ernest D. Buchanan, NASA Goddard Space Flight Ctr. (United States); Nicholas L. Chapman, Northwestern Univ. (United States); David T. Chuss, Villanova Univ. (United States); Jessie L. Dotson, NASA Ames Research Ctr. (United States); Dale J. Fixsen, NASA Goddard Space Flight Ctr. (United States); Mark Halpern, The Univ. of British Columbia (Canada); Louise A. Hamlin, Jet Propulsion Lab. (United States); Doyal A. Harper, The Univ. of Chicago (United States); Gene C. Hilton, National Institute of Standards and Technology (United States); Kent D. Irwin, Stanford Univ. (United States); Christine A. Jhabvala, NASA Goddard Space Flight Ctr. (United States); Attila Kovacs, California Institute of Technology (United States); Leslie W. Looney, Univ. of Illinois at Urbana-Champaign (United States); Stephen F. Maher, Science Systems and Applications, Inc. (United States); Timothy M. Miller, Samuel H. Moseley, NASA Goddard Space Flight Ctr. (United States); Giles Novak, Northwestern Univ. (United States); Enzo Pascale, Cardiff Univ. (United Kingdom); Marcus C. Runyan, Jet Propulsion Lab. (United States); Eric Sandberg, SOFIA / USRA (United States); Fábio P. Santos, Northwestern Univ. (United States); Elmer H. Sharp III, Leroy M. Sparr, NASA Goddard Space Flight Ctr. (United States); Johannes G. Staguhn, Johns Hopkins Univ. (United States); Carole E. Tucker, Cardiff Univ. (United Kingdom); Armen S. Toorian, Jet Propulsion Lab. (United States); Anthony D. Turner, Jet Propulsion Lab. (United States); Caesar Wirth, The Univ. of Chicago (United States); John E. Vaillancourt, SOFIA / USRA (United States); Edward J. Wollack, NASA Goddard Space Flight Ctr. (United States)

We describe the current status of HAWC+, the facility far-infrared camera and polarimeter for NASA's SOFIA airborne observatory. HAWC+ is scheduled to be commissioned in mid 2016, and we will report results from lab system testing and flight observations as available. HAWC+ uses two detectors in a dual-beam imaging polarimeter configuration, with both detectors consisting of 32x40 arrays of transition-edge sensors in a BUG architecture from Goddard, hybridized with SQUID time-domain multiplexers from NIST. The Multi-Channel Electronics system from UBC controls and reads out the detectors. The detectors are operated at 0.13 K via an Adiabatic Demagnetization Refrigerator backed by a 4He sorption cooler. HAWC+ observes in five continuum bands -- one at a time -- from 53 to 216 microns, offering angular resolution as fine as 5" (FWHM) when operated on the SOFIA telescope. A set of monochromatic half-wave plates modulate the input polarization for precise measurement.

9908-210, Session PS3

Design and building of a derotator for the 4 m DAG telescope

Onur Keskin, Isik Üniv. (Turkey); Laurent Jolissaint, HEIG-VD (Switzerland); Cahit Yesilyaprak, Atatürk Üniv. (Turkey); Sinan K. Yerli, Middle East Technical Univ. (Turkey)

Research in astrophysics always requires extremely sensitive and accurate instruments, whose development requires constant advances in all fields of technology. In particular, DAG (Eastern Anatolia Observatory in Turkish) telescope optical configuration has been designed to allow for a perfect mechanical stability of the focal plane instruments, while minimizing the size of the telescope mount structure and dome. DAG is Alt-Az mount with the instruments located on the static (still) Nasmyth platforms. A geometric consequence of this scheme is that the image of an astronomical object will rotate around the optical axis, at an average rate of one rotation per day. While this rotation rate is not large, it needs to be compensated: science exposures can last several hours, and any rotation will totally blur the science image. In this paper the preliminary design of a derotator that will be placed inside the telescope volume to serve all focal plans instruments while generating no additional optical errors on the optical beam, will be presented.

9908-211, Session PS3

The Zwicky transient facility observing system

Richard G. Dekany, Roger M. Smith, Eric C. Bellm, Justin Belicki, John L. Cromer, Alex Delacroix, Gina Duggan, Michael E. Feeney, David Hale, John R. Henning, Stephen Kaye, Thomas Kupfer, Daniel L. McKenna, Peter H. Mao, Patrick Murphy, Michael Porter, Daniel J. Reiley, Reed L. Riddle, Mitsuko Roberts, Hector Rodriguez, Jeff Zolkower, California Institute of Technology (United States); Timothy M. Goodsall, Jet Propulsion Lab. (United States)

The Zwicky Transient Facility (ZTF) Observing System (OS) is the optomechanical subsystem responsible for the data acquisition of ZTF as it conducts a forthcoming three-year wide-area, high-cadence time-domain survey. The ZTFOS consists of the Palomar 48 inch (1.2 meter) aperture Samuel Oschin Telescope and the ZTF Camera (ZTFC), a 47 square degree scientific imaging mosaic sporting sixteen 6k x 6k e2v CCD231-C6 arrays co-mounted on a common focal plate and integrated with four 2k x 2k STA3600 guide, focus, and flexure-compensation CCDs that have been processed 'delta doped' by Jet Propulsion Laboratory for improved sensitivity. Telescope updates include the figuring and installation of a new 50-inch diameter aspheric Schmidt plate, installation of a new instrument ring girder, spiders, and mounting hub, including a camera hexapod mount, and a new filter exchanger mechanism to manage ZTF's 500 x 480 mm optical filters.

9908-214, Session PS3

Wide field of view spectroscopy using solid Fabry-Perot interferometers

Jonathan Nikoleyczik, Univ. of Maryland, College Park (United States); Alexander S. Kutyrev, NASA Goddard Space Flight Ctr. (United States); Sylvain Veilleux, Univ. of Maryland, College Park (United States); Samuel H. Moseley, NASA Goddard Space Flight Ctr. (United States)

We present a telescope consisting of dual solid Fabry-Perot Interferometers. Each Fabry-Perot etalon is made of a single piece of L-BBH2 which has a high index of refraction n~2.07. Each is then coated to give a spectral resolution of R~30,000. Running the etalons in tandem reduces the overlapping orders and allows for a much wider free spectral range. Since the etalon thickness is fixed we use a thermal control system to tune the spacing of both etalons. Thermal changes occur in both thermal expansion and index of refraction which further enhances the FSR. The telescope then moves spatially in order to get spectral information at every point in the field of view. We then select spectral lines for further analysis and create maps of the line depths across the field. Using this technique we are able to measure the fluorescence of chlorophyll in plants and observe zodiacal light. In the chlorophyll analysis we are able to detect the presence of chlorophyll using the line depth in a plant using the sky as a reference solar spectrum. We also use a model of the Fabry-Perot system with an input spectrum to both model the observed output and further constrain the parameters of the etalons. This instrument has possible applications in either a cubesat or aerial observations to measure bulk plant activity over large areas.

9908-215, Session PS3

COATLI: an all-sky robotic optical imager with 0.3 arcsec image quality

Alan M. Watson, Salvador Cuevas Cardona, Luis C. Alvarez Nuñez, Fernando Ángeles, Rosa L. Becerra-Godínez, Oscar Chapa, Alejandro S. Farah, Jorge Fuentes-Fernández, Rosalía Langarica Lebre, Fernando Quirós, Carlos G. Román-Zúñiga, Jaime Ruíz, Carlos G. Tejada, Silvio J. Tinoco, Univ. Nacional Autónoma de México (Mexico)

COATLI is a new instrument and telescope that will provide 0.3 arcsec FWHM images from 550 to 900 nm over a large fraction of the sky. It consists of a robotic 50-cm telescope with a diffraction-limited imager. The imager has a steering mirror for fast guiding, a blue channel using a EMCCD from 400 to 550 nm to measure image motion, a red channel using a standard CCD from 550 to 920 nm, and an active optics system based on a deformable mirror to compensate static and slow aberrations in the red channel. Since the telescope is small, fast guiding will provide diffraction-limited image quality in the red channel over a field of at least 1 arcmin and with coverage of a large fraction of the sky, even in relatively poor seeing. The COATLI telescope will be installed at the Observatorio Astronómico Nacional in San Pedro Mártir, Baja California, México, in February 2016 and will operate initially with a simple interim imager. The definitive COATLI instrument will be installed at the start of 2017.

The reference science programs for COATLI are characterized by requiring optical imaging with better-than-seeing image quality and either large amounts of observing time or time-critical observations. They include observations to place GRBs in the context of their host galaxies, photometry of eclipses in the Orion Trapezium, and broad searches for low-mass companions.

The principal technological challenge of COATLI has been producing a high-performance diffraction-limited imager with two channels, fast guiding, and active optics while meeting the strenuous envelope and mass budget (35 kg) of the small telescope.

In this contribution, we will present the basic theory of diffraction-limited performance using fast guiding on small telescopes, highlight the enabling technologies and technological innovations, present our reference science cases, discuss the state of the project and our future plans, and speculate on future developments.

Accompanying poster presentations by Jorge Fuentes-Fernández and Salvador Cuevas will discuss technical aspects of the instrument in more detail.

9908-216, Session PS3

Optical design of COATLI: an all-sky robotic optical imager with 0.3 arcsec image quality

Jorge Fuentes-Fernández, Salvador Cuevas Cardona, Oscar Chapa, Alan M. Watson, Univ. Nacional Autónoma de México (Mexico)

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We present the details of the optical design of the instrument, which requires two intermediate pupil planes and must meet the tight envelope size and mass requirements for the small telescope. COATLI is based on collimator-camera pairs using achromatic doublets. Along with the optical design, we present the efficiency, tolerance and thermal studies, necessary to ensure excellent image quality in both channels.

9908-217, Session PS3

Systems design of COATLI: an all-sky robotic optical imager with 0.3 arcsec image quality

Salvador Cuevas Cardona, Alan M. Watson, Luis C. Álvarez-Núñez, Fernando Ángeles, Rosa L. Becerra-Godínez, Oscar Chapa, Alejandro S. Farah, Jorge Fuentes-Fernández, Rosalía Langarica Lebre, Fernando Quiróz, Carlos G. Román-Zúñiga, Jaime Ruiz, Carlos G. Tejada, Silvio J. Tinoco, Univ. Nacional Autónoma de México (Mexico)

COATLI is a new instrument and telescope that will provide 0.3 arcsec FWHM images from 550 to 900 nm over a large fraction of the sky. It consists of a robotic 50-cm telescope with a diffraction-limited imager. The imager has a steering mirror for fast guiding, a blue channel using a EMCCD from 400 to 550 nm to measure image motion, a red channel using a standard CCD from 550 to 920 nm, and an active optics system based on a deformable mirror to compensate static and slow aberrations in the red channel. Since the telescope is small, fast guiding will provide diffraction-limited image quality in the red channel over a field of at least 1 arcmin and with coverage of a large fraction of the sky, even in relatively poor seeing. The COATLI telescope will be installed at the Observatorio Astronómico Nacional in Baja California, México, in February 2016 and will operate initially with a simple interim imager. The definitive COATLI instrument will be installed at the start of 2017.

The principal technological challenge of COATLI has been producing a high-performance diffraction-limited imager with two channels, fast guiding, and active optics while meeting the strenuous envelope and mass budget (35 kg) of the small telescope. Furthermore, the system is robotic and previsions must be taken in account to operate under the observatory environment with minimum maintenance work.

In this work we present the general mechanics, electro-mechanics and opto-mechanics design of COATLI including telescope installations and instrument.

9908-218, Session PS3

Conception of a near-IR spectrometer for ground-based observations of massive stars

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Massive stars are very hot and luminous stars which have a tremendous impact on their surroundings via their powerful stellar winds and huge UV luminosities. The combination of these winds, the strong ionizing radiation fields as well as the death of these stars in gigantic supernova explosions make massive stars key players for the evolution of the Universe. The full understanding of astrophysical sources requires access to a rather broad range of wavelengths. Every wavelength domain provides another specific piece of information that is needed to solve the puzzle. The near-IR domain around 1 ?m has an enormous diagnostic potential for stellar activity and winds. Indeed, this domain contains many spectral lines whose profiles provide useful information about these phenomena over almost the entire range of stellar masses. Although those wavelengths can be observed from the ground, this region is somewhat neglected due to technological issues such as the decrease in sensitivity of conventional CCD detectors in that spectral domain.We have designed a near-infrared spectrograph to partially bridge the gap in this area. The final location of the spectrograph will be the vacant Nasmyth focus of the TIGRE telescope in La Luz, Mexico. The instrument's interface consists in a fiber-bundle that feeds the collimator mirror with stellar light from the telescope. On the other hand, a simultaneous sky background measurement is accomplished through the use of dedicated fibers surrounding the central ones, which are located near the target position within the telescope focal plane. This configuration also allows the analysis of multiple target spectra in case of crowded fields such as stellar clusters.In our contribution, we outline the different steps in the design of the instrument. Starting from the derivation of theoretical relationships from the scientific requirements and telescope characteristics, the entire optical design of the spectrograph is presented. Specific optical elements, such as a toroidal lens, are introduced to improve the instrument's performances. Then, the verification of predicted optical performances is investigated through optical analyses such as resolution checking and tolerancing process. Straylight calculations and the calibration unit of the instrument are discussed as well. Eventually, the star positioning system onto the central fiber core is explained in details. This latter incorporates a back-illuminating system of the fiber bundle with the help of a LED located inside the spectrograph housing.

9908-219, Session PS3

LSST camera grid structure made out of ceramic composite material, HB-Cesic

Matthias Krödel, ECM Engineered Ceramic Materials GmbH (Germany); J. Bryan Langton, SLAC National Accelerator Lab. (United States)

LSST is constructing a digital astronomical camera for inclusion in a new observatory. The current schedule for first light is 2020. The LSST

Telescope will have an f1.2 optic and the camera will have 65 cm diameter, 3.2 Giga-pixel focal plane constructed out of a mosaic of 189 science CCD sensors and 12 wave front guider sensors. The main camera structure will be constructed out of a ceramic material called HB-Cesic supplied by ECM, Germany in order to ensure the required stiffness and thermal stability for this challenging focal plane structure.

In this paper we are presenting the ceramic design and the fabrication of the camera structure which is using the unique manufacturing features of the HB-Cesic technology associated with a dedicated metrology device in order to ensure the challenging flatness requirement of 4 micron over the full array.

9908-221, Session PS3

The Fly's Eye camera system: new results with an autonomously observing telescope

László Mészáros, András Pal, Attila Jaskó, Krisztián Vida, Katalin Oláh, Gergely L. Csépány, György Mez?, MTA Research Ctr. for Astronomy and Earth Sciences (Hungary)

The Fly's Eye camera system is a multiple-passband full-sky surveying instrument employing 19 wide-field cameras in a mosaic arrangement on a spherical frame. The cameras are equipped with fast focal ratio lenses and Sloan filters. With this setup we intend to perform time-domain astronomy and observe several kind of astronomical phenomena. The cameras are supported by single mount, while the sidereal tracking, i.e. the compensation for the apparent celestial rotation is performed by a hexapod mount. As discussed in our earlier design-related publications, this tracking is unavoidable when considering 0.3 gigapixel imaging, a field-of-view diameter of 120 degrees and exposure times around a few minutes.

As we demonstrated (see e.g. Jasko et al., 2014, SPIE), this small-scale hexapod design is capable of perform positioning and tracking accuracy of the cameras at the level of an arcsecond, much better than the imaging resolution of the optics (which is 20 arcseconds per pixel). Due to the extremely large simultaneous field-of-view, this accuracy is needed in all of the three rotational degrees of freedom. Hence, the hexapod is an ideal choice to perform a location-independent way to accomplish the aforementioned requirements. This platform has many additional advantages: the redundancy of the hexapod allows smooth operations even if one or two of the legs would stuck. It can calibrate itself by performing astrometry on the detected stars without the need of polar (or any kind of) alignment.

In this presentation we present the details of the performance of the full Fly's Eye Camera System. Currently Fly's Eye is mounted at Piszkés-tet? Observatory in a thermally stabilized protective enclosure. Autonomous observations are performed whenever weather permits, the decision itself is based on the real-time analysis of ambient data and sky quality analysis of all-sky cameras. Here we detail the specifications of the camera-filter-lens optical setup and the custom solutions for fault-tolerant embedded control of the imaging subsystem. As we present here, even with this small-scale optics the accurate sidereal tracking is sufficient to reach millimagnitude precision at the bright-end while the detection of faint sources down to r=15 is also feasible. Scientific data series are then provided for all the five standard Sloan filters while the frequency of filter usage is proportional to the camera quantum efficiency. Namely, every second frame is Sloan r', every 6th is i' and g' while u' and z' have a period of 12 frames. This type of data acquisition setup can be exploited in scientific analysis rather efficiently since the aforementioned scheme is equivalent to high sampling rate of flux measurements and low sampling information about color variations.

The main goal of our project is to provide series of data of continuously monitored various astronomical phenomena, including solar system objects, variability of stars with magnetic activity, transiting exoplanets and bright extragalactic transients. The Fly's Eye camera system provides a complementary dataset to large synoptic surveys (e.g. LSST) since the saturation limit of these instruments is close to faint limit of the Fly's Eye's.

9908-222, Session PS3

An airborne infrared spectrometer for solar eclipse observations

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This paper presents the design of an innovative solar spectrometer that will fly on the NSF/NCAR High-Performance Instrumented Airborne Platform for Environmental Research (HIAPER) Gulfstream V during the 2017 solar eclipse. The airborne infrared spectrometer (AIR-Spec) is groundbreaking in two aspects: it will image infrared coronal emission lines that have never been measured, and it will bring high resolution imaging to the HIAPER GV.

The instrument development faces the challenges of achieving adequate spectral and spatial resolution in a compact package mounted to a noisy moving platform. To ensure that AIR-Spec meets its research goals, the instrument is undergoing pre-flight modeling and testing. The results are presented with reference to the instrument requirements.

The solar magnetic field enables the heating of the corona and provides its underlying structure. Energy stored in coronal magnetic fields is released in flares and coronal mass ejections and ultimately drives space weather. Therefore, direct measurements of the coronal magnetic field have significant potential to enhance understanding of coronal dynamics and improve solar forecasting models. Of particular interest are observations of coronal field lines in the transitional region between closed and open flux systems, providing important information on the origin of the slow solar wind.

While current instruments routinely observe only the photospheric and chromospheric magnetic fields, AIR-Spec will take a step toward the direct observation of coronal fields by measuring plasma emission in the infrared at high spatial and spectral resolution. During the total solar eclipse of 2017, AIR-Spec will observe five magnetically sensitive coronal emission lines between 1.4 and 4 μm from the HIAPER GV at an altitude above 14.9 km. The instrument will measure emission line intensity, width, and Doppler shift, map the spatial distribution of infrared emitting plasma, and search for waves in the emission line velocities.

AIR-Spec consists of an optical system (feed telescope, grating spectrometer, and infrared detector) and an image stabilization system. The telescope collects light over a 0.4 degree (1.5 solar radius) field of view and feeds it into the spectrometer, which is based on a planar diffraction grating operating near the Littrow condition. The five wavelengths of interest are divided into two channels and imaged onto the cryogen-cooled InSb detector.

The image stabilization system uses a fast steering mirror to correct the line-of-sight for platform perturbations. The mirror command is calculated as a combination of four inputs: the eclipse ephemeris, GPS location, aircraft attitude measured by a set of fiber-optic gyroscopes, and residual drift correction from an operator-controlled joystick. The visible context images that allow the operator to correct for drift will also be used post-flight for spatial registration of the spectrometer data.

9908-223, Session PS3

Project PANOPTES: a citizen-scientist exoplanet transit survey using commercial digital cameras

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Project PANOPTES (http://panoptes.github.io/) is aimed at establishing a collaboration between professional astronomers, citizen scientists and schools to discover a large number of exoplanets with the transit technique. We have developed digital camera based imaging units to image large parts of the sky and look for exoplanet transits. Each unit costs approximately US$5000, and runs robotically every night. By using low-cost, commercial DSLR cameras, we have developed a uniquely cost-efficient system for wide field astronomical imaging, offering approximately two orders of magnitude better etendue per unit of cost than professional wide-field surveys. Our vision is to have thousands of these units built by schools and citizen scientists gathering data, making this project the most productive exoplanet discovery machine in the world. The full power of the project comes from combining many images, acquired by different units, to increase accuracy and uncover smaller planets. PANOPTES is both a science project and an outreach project, and our ultimate goal is to crowdsource exoplanet discoveries to the public.

We provide a technical description of the project, including the photometric data processing approach we developed to handle RGB color detector arrays, usually known as Bayer arrays. We discuss the expected science output of the network and its current status, including image processing and data handling.

9908-33, Session 8

Hyper Suprime-Cam *(Invited Paper)*

Satoshi Miyazaki, National Astronomical Observatory of Japan (Japan)

Hyper Suprime-Cam (HSC) is a new 1.5 degree field diameter camera built for Subaru prime focus, which realizes seeing limited imaging on Mauna Kea (~ 0.6 arcsec median in i-band) over the entire field of view. HSC began the science observation on March 2014 and the steady operation is fulfilled; nearly 75 % of the night time (expect cloudy night)is used for target exposures. Half of HSC night is allocated for a 5 years legacy survey (HSC survey) and the rest is allocated for general observers including Keck/Gemini communities through the time exchange program. The primary science driver of the HSC survey is cosmology which makes use of weak lensing technique. Thanks to the combination of large aperture and high resolution imaging, the number density of resolved galaxies suited for lensing analysis is quite high (near 40 galaxies per square arc minute). This unique features enables high resolution weak lensing mass map where we could detect the dark matter halo peaks of galaxy cluster scales. We expect stronger cosmological constraints from this halo count combined with the standard two point shear statistics. In this talk, we will present the outline of the camera and highlights of early science results.

9908-34, Session 8

HiPERCAM: a high-speed quintuple-beam CCD camera for the study of rapid variability in the universe

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HiPERCAM is a high-speed camera for the study of rapid variability in the Universe. The project is funded by a 3.5 Meuro European Research Council Advanced Grant. HiPERCAM builds on the success of our previous instrument, ULTRACAM, with very significant improvements in performance thanks to the use of the latest technologies. HiPERCAM will use 4 dichroic beamsplitters to image simultaneously in 5 optical channels covering the u', g', r', i', z' bands. Frame rates of over 1000 per second will be achievable using the ESO CCD controller (NGC), with every frame GPS timestamped. The detectors are custom-made frame-transfer CCDs from e2v, with 4 low-noise (2.5e-) outputs, mounted in small thermoelectrically-cooled heads operated at 180 K, resulting in virtually no dark current. The two reddest CCDs will be deep-depletion devices with anti-etaloning, providing high quantum efficiencies across the red part of the spectrum with no fringing. The instrument will also incorporate scintillation noise correction via the conjugate-plane photometry technique. The opto-mechanical chassis will make use of additive manufacturing techniques in metal to make a lightweight, rigid and temperature-invariant structure. First light is expected on the 4.2m William Herschel Telescope on La Palma in 2017 (on which the field of view will be 10' with a 0.3"/pixel scale), with subsequent use planned on the 10.4 Gran Telescopio Canarias on La Palma (on which the field of view will be 4' with a 0.11"/pixel scale) and the 3.5m New Technology Telescope in Chile.

9908-36, Session 8

The PAU camera at the WHT

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The PAU Camera is a novel instrument equipped with a system of 40 narrow-band (12.5 nm wide in spots of 10 nm) filters spanning the wavelength range from 450 nm to 850 nm, and with 6 wide-band filters (u, g, r, i, z, Y). It aims at observing ~100 deg2 of sky and provide up to 3 million redshifts to i(AB)~22.5 with a z-uncertainty of ~ 3 per mill, in which shape and deep Broad-Band photometric measurements have already been obtained by CFHTLenS and KIDS, an in which spectroscopic redshifts for calibration are available from the GAMA, VIPERS, DEEP2 and zCOSMOS redshift surveys. The survey will be a few magnitudes deeper than current completed large flux limited surveys (such as Gamma) and 10 times larger than current completed deep flux limited surveys (such as VVDS/VIPERS/Deep2).

The survey data will enable the study of target selections incompleteness and improve Broad Band photo-z estimates (in KIDS, DES and Euclid) to reach the accuracy required for large-scale clustering and weak lensing analysis, produce the most detailed studies of intermediate-scale cosmic structure analysis, provide the first precise measurement of intrinsic alignment at z~0.75 and enable cross-correlation techniques for redshift measurements, magnification and sampling variance cancelation studies.

The camera is installed at the William Herschel Telescope. The focal plane, composed of 18 Hamamatsu photonics 2k x 4 k 200 microns thick fully depleted CCD's covers ~1 deg2 FoV, every 15 micron pixel corresponding to 0.26''. The PAU Camera is a technologically pioneer instrument built with a large carbon fiber enclosure in order to minimize weight at the WHT prime focus. Since the 8 central CCd's cover the observation of the 40 Narrow Band filters, a system of five movable filter trays is installed. In order to minimize the dead areas in the focal plane, the filter trays are located as close as possible to the CCD's inside the cryostat. The cryogenic system includes a dual system: a Nitrogen system to make a fast cool down during installation of the instrument and a cryocooler system to maintain the operational temperature during the observations.

During survey observation mode, the PAU Camera generates around 250 GBytes of data per night. Every image is analyzed by an online monitoring system controlled by the Camera Control system. The PAU Data management system transfers the data and archives it at Portal Informacio Cientifica (PIC) in Barcelona, where the data calibration and processing takes place in order to produce a science-ready catalog. The first processing is done in an automatic nightly pipeline in order to provide fast feedback during the observation periods.

The PAU Camera saw first light on June 3rd, 2015 and, since then, has had several observation periods in which has covered portions of different fields (DEEP2, zCOSMOS, W1, W4,...). This talk gives an overview of the camera and its systems and describes its performance and preliminary scientific results obtained after the commissioning and the various observation periods during the last year.

9908-37, Session 8

A near-infrared SETI experiment: commissioning, data analysis, and performance results

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Over the last two decades optical SETI experiments have been conducted to search for either continuous or pulsed optical laser beacons used for interstellar communication or energy transmission. Near-infrared bandwidth offers a compelling window for signal transmission since there is a decrease in interstellar extinction and Galactic background compared to optical wavelengths. An innovative Near-InfraRed SETI (NIROSETI) instrument has been designed and build to take advantage of a new generation of fast (> 1 Ghz) low-noise near-infrared avalanche photodiodes to search for nanosecond near-infrared (850 - 1650 nm) pulses. The instrument was successfully installed and commissioned at the Nickel telescope (1m) at Lick Observatory in March 2015. We will describe the overall design of the instrument with a focus on the new analysis methods developed for data acquisition and reduction for near-infrared SETI. Time and height analyses of the pulses produced by the detectors are performed to search for periodicity and coincidences in the signals. We will further discuss our SETI survey plans and strategy.

9908-212, Session 8

Performance of the e2v 1.2 GPix cryogenic camera for the J-PAS 2.5m survey telescope

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The J-PAS project will perform a five-year survey from a new 2.5m telescope in Teruel, Spain. The build and factory testing of the commercially supplied cryogenic camera are described. The 1.2 Giga-pixel focal plane is contained within a novel LN2 vacuum cryostat, which maintains the flatness of the 0.45m diameter focal plane to better than 40 µm peak to valley. The focal plane temperature operates at a temperature of -100oC with a variation across the focal plane of better than 10oC and a stability of better than +/- 0.5 oC over long operational periods. The proximity drive electronics is designed to achieve a 5 e- readout noise from the 224-channel CCD system.

e2v technologies have designed and are supplying the camera unit and cooling facility (CryoCam). CryoCam forms a part of the JPCam, which also includes the mechanical subsystem on the telescope, including the shutter and filter assemblies. Cryocam utilises fourteen 82 Megapixel science CCDs, together with peripheral wavefront and autoguider devices, on a precision focal plane, and must operate with high performance and minimum maintenance for at least ten years. All design reviews have been completed for Cryocam and the assembly, integration, verification and test phase of the program is nearing completion. This paper describes how the challenging user requirements have been met by Cryocam, including the demanding mechanical and cooling requirements. Results from the testing activities are presented, including the advanced metrology performed on the focal plane, and cooling trials performed to date. The final paper will include results from most of the verification activities.

Details of the CryoCam have been presented at previous conferences. The e2v camera consists of the following main components; sets of three CCD types in custom packages (14 9kx9k e2v CCD209-99 science devices, 8 2kx2k e2v CCD44-82 frame transfer devices (wavefront sensing) and 4 1kx1k e2v CCD47-20 devices (autoguiders) mounted on a precision focal plane cold plate, a cryogenic vacuum cryostat with precision kinematic mounts for the focal plane, liquid nitrogen delivery and control system, local low-noise electronics, CCD interface electronics and data transfer electronics, all designed for this application, interfaces to mounting system and telescope, together with system control software and API for camera operation.

The following main items will be presented- Opto-mechanical design, mechanical trials and metrology; instrument control and support subsystem; thermal trials; electronic CCD control and readout with impressive readout noise performance data; instrument status and final integration and test results prior to delivery

9908-38, Session 9

CARMENES: an overview six months after first light

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This paper gives an overview of the CARMENES instrument and of the survey that will be carried out with it. More detailed accounts of individual subsystems are given in a set of accompanying papers. CARMENES (Calar Alto high-Resolution search for M dwarfs with Exo-earths with Near-infrared and optical Echelle Spectrographs) is a next-generation instrument that has been built for the 3.5m telescope at the Calar Alto Observatory by a consortium of eleven Spanish and German institutions. The scientific goal of the project is conducting a 600-night radial-velocity survey targeting ~300 M dwarfs with the completed instrument. With a precision of 1 m/s, which is the goal of CARMENES, it will be possible to detect Earth-like planets in the habitable zones of these stars.

The CARMENES instrument consists of two separate échelle spectrographs covering the wavelength range from 0.55 to 1.7 ?m at a spectral resolution of R = 82,000, fed by fibers from the Cassegrain focus of the telescope. The CARMENES instrument consists of two spectrographs, one equipped with a 4k x 4k pixel CCD for the range 550 to 1050 nm, and one with two 2k x 2k pixel HgCdTe detectors for the range from 1.0 to 1.7 ?m. Each spectrograph is coupled to the 3.5m telescope with two optical fibers. The front end contains a dichroic beam splitter and an atmospheric dispersion corrector, to feed the light into the fibers leading to the spectrographs. Guiding is performed with a separate camera; on-axis as well as off-axis guiding modes are implemented. Fibers with octagonal cross-section are employed to ensure good stability of the output in the presence of residual guiding errors. The fibers are continually actuated to reduce modal noise. Additional fibers are available for simultaneous injection of light from emission line lamps or alternatively from a thermally stabilized Fabry-Pérot etalon for RV calibration. The spectrographs are mounted on benches inside vacuum tanks located in rooms, which have been equipped with temperature control systems. Due to the large thermal mass of the optical benches, their temperatures do not drift by more than ±0.01°C over 24h. The visible-light spectrograph is operated near room temperature, the NIR spectrograph is cooled to ~140K.

The subsystems of CARMENES were integrated in Heidelberg and Granada, and moved to Calar Alto in the course of 2015. The completed instrument saw “First Light” at the telescope on Nov 9, 2015, which marks the first time that a radial-velocity instrument optimized for the red and near-infrared wavelength ranges has been put into operation. Further technical tests and collection of data for the characterization of the instrument performance took place during November and December.

The data reduction pipeline for CARMENES has been developed in parallel with the instrument hardware. It has been shown to deliver radial velocities with m/s precision on HARPS data, and is now being optimized for processing the on-sky data from both CARMENES spectrographs. Further work will be done on the calibration procedures, and on the algorithms used for subtracting telluric contamination.

9908-40, Session 9

The habitable-zone planet finder: AI&V status and summary of research and development to achieve high precision NIR Doppler radial velocities

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The Habitable-Zone Planet Finder is a stabilized, fiber-fed, NIR spectrometer built for the 10m Hobby-Eberly telescope (HET) built from the ground up to be capable of discovering low mass planets around mid-late M dwarfs. The optical design of the HPF is an asymmetric white pupil spectrograph layout in a vacuum cryostat cooled to 180 K. The spectrograph uses gold-coated mirrors, a mosaic echelle grating, and a single Teledyne Hawaii-2RG (H2RG) NIR detector with a 1.7-micron cutoff covering parts of the information rich z, Y and J NIR bands at a spectral resolution of R~50,000. The use of 1.7 micron H2RG enables HPF to operate warmer than most other cryogenic instruments. In addition to summarizing the AI&V status and commissioning plans, we outline the results of the several R&D projects that were necessary to assure we will meet our science requirements. We present and summarize the main challenges to achieving precision radial velocities in the NIR, and the high level of R&D effort by our team to solve these problems, including sub-milli Kelvin (RMS) temperature control with bespoke electronics, a very high pressure stability at better than 10^-7 torr, and a double scrambler to achieve both near and far-field fiber scrambling, We also discuss the impact of stellar activity and how the NIR helps mitigate these issues, but also how design choices have been made to ensure that the chosen NIR bandpass contains suitable activity indicators.

9908-41, Session 9

WISDOM: the WIYN spectrograph for Doppler monitoring: a NASA-NSF concept for an extreme precision radial velocity instrument in support of TESS

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The Kepler mission highlighted that precision radial velocity (PRV) follow-up is a real bottleneck in supporting transiting exoplanet surveys. The limited availability of PRV instruments, and the desire to break the "1 m/s" precision barrier, prompted the formation of a NASA-NSF collaboration 'NN-EXPLORE' to call for proposals designing a new Extreme Precision Doppler Spectrograph. By securing a significant fraction of telescope time on the 3.5m WIYN at Kitt Peak, and aiming for unprecedented long term precision, this instrument will provide a unique tool for U.S. astronomers in characterizing exoplanet candidates identified by TESS. One of the two funded instrument concept studies is led by the Massachusetts Institute of Technology, in consortium with Lincoln Laboratories, Harvard-Smithsonian Center for Astrophysics and the Carnegie Observatories. This paper describes the instrument concept WISDOM (WIYN Spectrograph for DOppler Monitoring) prepared by this team.

WISDOM is a fiber fed, environmentally controlled, high resolution (R=110k), asymmetric white-pupil echelle spectrograph, covering a wide 380-1300nm wavelength region. Its R4 and R6 echelle gratings provide the main dispersion, symmetrically mounted on either side of a vertically aligned, vacuum-enclosed optical bench. Each grating feeds two cameras and thus the resulting wavelength range per camera is narrow enough that the VPHG cross-dispersers and employed anti-reflection coatings are highly efficient. The instrument operates near room temperature, and so thermal background for the near-infrared arm is mitigated by thermal blocking filters and a short (1.7 micron) cutoff HgCdTe detector. To achieve high resolution while maintaining small overall instrument size (100/125mm beam diameter), imposed by the limited available space within the observatory building, we chose to slice the telescope pupil 6 ways before coupling light into fibers. An atmospheric dispersion corrector and fast tip-tilt system assures maximal light gathering within the 1.2" entrance aperture. The six octagonal fibers corresponding to each slice of the pupil employ ball-lens double scramblers to stabilize the near- and far-fields. Three apiece are coupled into each of two rectangular fibers, to mitigate modal nose and present a rectilinear illumination pattern at the spectrograph's slit plane. Wavelength solutions are derived from ThAr lamps and an extremely wide coverage dual-channel laser frequency comb. Data is reduced on the fly for evaluation by a custom pipeline, while daily archives and extended scope data reduction products are stored on NExScI servers, also managing archives and access privileges for GTO and GO programs.

Note: individual papers, submitted along this main paper, describe the details of subsystems such as the optical design, the environmental control system, the fiber link design, and the pupil slicer.

9908-42, Session 9

The Hobby Eberly Telescope high resolution spectrograph upgrade

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The Hobby Eberly Telescope (HET) High Resolution Spectrograph (HRS) has been inefficiently coupled to the HET since commissioning in 2001, leading to low throughput performance. A significant upgrade is being commissioned during mid-2015. The two surface-relief cross dispersers have been replaced with four VPHGs for wavelength dependent throughput gains between 1.5x and 3x. The VPHG cross dispersers give greater interorder separation (IOS) to support simultaneous object-fiber and sky-fiber image slicers for net throughput gains of 2.1x, 4.5x, and 8.2x at resolving powers 35,000, 70,000, and 105,000, respectively. Sky subtraction capabilities have been added and enhanced considerably. Additionally, octagonal optical fibers have been added along with new auxiliary instrumentation including a fiber mode scrambler, fiber double scramblers, a two-channel exposure meter with bandpass filters, and enhanced temperature stabilization of the instrument. HRS is a reconfigurable spectrograph, operated essentially every clear night in queue scheduled mode, and reconfigured multiple times per night. The upgrade is engineered for reliability, plus the ability to reconfigure with precision repeatability. To maintain spectral coverage with the increased IOS, HRS will become a double spectrograph with the reconfiguration of the previous single arm as the red arm, and the future addition of a blue arm. The blue arm extends the spectral coverage from ~410 nm to 362 nm to broaden the scientific capabilities of HRS, particularly for metal poor star science.

This paper gives the novel engineering details of the HRS upgrade, the new instrument configurations and capabilities, and a performance analysis of the upgraded HRS.

9908-43, Session 9

Performance verification of infrared Doppler for the Subaru Telescope

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Infrared Doppler (IRD) is an instrument mainly dedicated to a search for Earth-mass planets around nearby M-dwarfs by precise radial velocity measurement in the near-infrared. We report the current status of the IRD instrument development witch is under the final phase of assembly, integration and test. A first light is expected to be done in the middle of 2016 at the Subaru telescope, and a large strategic survey program, 100 nights for 5 years, will be conducted to detect various planets down

to one-Earth mass in their habitable zone. IRD employs many original technologies to achieve ultimate radial velocity measurement stability. The spectrometer consists of a R6 Echelle grating and VPH to achieve a spectral resolution of 70,000 at maximum, covering Y, J, H-bands simultaneously with 2xH2RG detectors. IRD is a fiber-fed spectrometer with a high pointing stability thanks to Adaptive Optics of the Subaru telescope on the Nasmyth platform. Two fibers can be used simultaneously to record spectrum of a star and wavelength reference source, a laser frequency comb. Either a combination of 2 multi-mode fibers, or a multi-mode and single-mode fiber, or 2x single-mode fibers can be used. Thanks to the AO system, a star-light can be injected into a single-mode fiber if a target is bright, without a modal-noise. The spectrometer itself will be placed in a Coude room for good temperature stability. A newly developed laser frequency comb can cover almost Y,J,H-bands with 12.5 GHz frequency span better than 0.3 m/s stability. An ultra-low CTE ceramic component is employed for an optical table, off-axis parabola a flat mirror including their holders, and a slit holder to minimize the effect of temperature variation. Various types of mode scramblers based on a fiber, both static and dynamic, to reduce modal noise which is a major error source in radial velocity measurements in NIR. The instrument will be shipped to the University of Hawaii, instituted of Astronomy to assemble 2xH2RG array detectors, then a final stability test will be done to demonstrate radial velocity measurement precision better than 1m/s.

9908-44, Session 10

The Gemini High-Resolution Optical SpecTrograph (GHOST)

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The Gemini High-Resolution Optical SpecTrograph (GHOST) is the newest instrument chosen for the Gemini telescopes. It is being developed by a collaboration between the Australian Astronomical Observatory (AAO), the NRC - Herzberg in Canada and the Australian National University (ANU). Using recent technological advances and several novel concepts it will deliver R=50,000 and R=75,000 spectroscopy for up to 2 objects simultaneously. Ghost uses a fiber-image-slicer to allow for a much smaller spectrograph than that described by the resolution-slit–width product. With its fiber feed, we expect GHOST to have a sensitivity in the wavelength range between 363-950 nm that equals or exceeds that of similar directly-fed instruments on world-class facilities. GHOST has entered the build-phase. We report the status of the instrument and describe the technical advances and the novel aspects, such as the lenslet-based slit reformatting. Finally, we describe the unique scientific role this instrument will have in an international context, from exoplanets through to the distant Universe.

9908-45, Session 10

Development and construction of MAROON-X

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We report on the development and construction of a new fiber-fed, red-optical (500-900 nm), high-precision radial-velocity spectrograph for the 6.5 m Magellan Telescope in Chile. MAROON-X will be optimized to find and characterize rocky planets around nearby M-dwarfs with an intrinsic per measurement precision of <1m/s. The instrument is based on a commercial echelle spectrograph, a dual-arm KiwiSpec R4-100, customized for high stability and throughput. Thanks to its 100mm beam diameter, anamorphic pupil compression, and dual arm design, the core spectrograph is extremely compact. To achieve a spectral resolving power of R~80,000, we developed a 3x pupil slicer with incorporated double scrambler, based on micro-lens arrays. A laser-locked etalon comb calibrator, developed in house, features a long-term traceable stability of better than 10 cm/s. The core spectrograph with one arm is scheduled for delivery to Chicago in August 2016. A dedicated lab with a tightly temperature controlled environmental enclosure is in place to house the spectrograph and permit extensive lab tests in the second half of 2016. Depending on available funding, MAROON-X could be completed in 2017 and deployed at the Magellan Telescope as early as Q1/2018.

9908-46, Session 10

iLocater: An AO-fed Doppler spectrometer for the Large Binocular Telescope

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Radial velocity (RV) instruments have been stuck at 1 m/s precision for many years. The reason that overcoming the “1 m/s barrier” is so difficult is that several physical effects become relevant at the same level, creating a complicated systems engineering challenge. A promising path for mitigating the issues that prevent RV spectrographs from reaching their full potential involves using adaptive optics to achieve diffraction-limited performance.

We are building an ultra-precise Doppler instrument for the Large Binocular Telescope (LBT) named “iLocater.” Unlike previous spectrographs which are seeing-limited, iLocater uses single mode fibers and will operate behind an “extreme” adaptive optics system. With a spectral resolution that exceeds R=150,000 in the YJ bands, iLocater will deliver sub-meter-per-second precision when observing nearby stars; it is particularly well-suited for TESS follow-up observations of terrestrial planets located in or near the habitable zone. In this talk, I will explain why planet-finding spectrometers should use adaptive optics. I will also provide an update on our progress designing, building, and testing iLocater. Owing to the fact that the instrument is diffraction-limited and therefore decoupled from the influence of the telescope, the iLocater concept could be identically “cloned” for other adaptive optics facilities.

9908-47, Session 10

GIARPS: the unique VIS-NIR high precision radial velocity facility in this world

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GIARPS (GIAno & haRPS) is a project devoted to have on the same focal station of the Telescopio Nazionale Galileo (TNG) both the high resolution spectrographs HARPS-N (VIS) and GIANO (NIR) working simultaneously. This could be considered the first and unique worldwide instrument providing cross-dispersed echelle spectroscopy at a resolution of 50,000 and over in a wide spectral range (0.383 - 2.45 μm) in a single exposure. The science case is very broad, given the versatility of such an instrument and the large wavelength range. A number of outstanding science cases encompassing mainly extra-solar planet science starting from rocky planet search and hot Jupiters, atmosphere characterization can be considered. Furthermore both instrument can measure high precision radial velocity by means the simultaneous thorium technique (HARPS - N) and absorbing cell technique (GIANO) in a single exposure. Other science cases are also possible. Young stars and proto-planetary disks, cool stars and stellar populations, moving minor bodies in the solar system, bursting young stellar objects, cataclysmic variables and X-ray binary transients in our Galaxy, supernovae up to gamma-ray bursts in the very distant and young Universe, can take advantage of the unicity of this facility both in terms of contemporaneous wide wavelength range and high resolution spectroscopy.

9908-48, Session 10

Precision radial velocities with inexpensive compact spectrographs

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The high-precision astronomical spectrographs routinely employed to detect planets via the radial velocity method are generally large expensive instruments. We present our progress developing a comparable compact spectrograph using commercial 'off-the-shelf' components that can achieve similar precision at a fraction of the cost and complexity.

The spectrograph, PIMMS Visible, has an effective resolving power of R-50,000 and is capable of operating from 550nm to 750nm. The spectrograph is fed by a single length of a 19 multi-core fibre (MCF). One end of the fibre has been fused into a Photonic Lantern, a multi-mode to single-mode converter, whilst the other is used directly as the single-mode spectrograph slit (TIGER mode hexagonal grid). The multi-mode end is then either attached to a conventional telescope injection system for stellar observations or to a Thorlabs CCSA2 cosine corrector for solar observations (the later method allows for a 'full-disk' spectrum of the Sun whilst also limiting the amount of light collected).

We use a Rb locked single-mode (SMF) Fabry-Perot etalon as a simultaneous calibration source. The etalon spectrum calibration source is introduced into the MCF fibre via a novel side coupled tapered SMF, and thus superimposed on the object spectrum. This is achieved by tapering the output fibre of the etalon such that it ceases to guide light. The tapered etalon fibre is then wrapped around a portion of the MCF which has had its cladding removed, thus allowing the etalon frequency combs light to be coupled to the cores of the MCF.

With this setup we obtain an RMS velocity precision of 1m/s when calibrating with the fibre etalon (which is stabilised to less than a few 10's cm/s). We demonstrate the power and stability of our approach through high cadence spectroscopy of the Sun. With a few hours of continuous observations, we detect the solar p-mode oscillations (also known as the 5-minute oscillations). We will also present a series of observations re-detecting exoplanets with known radial velocities.

9908-39, Session PS4

Stability of the FOCES spectrograph using an astro-frequency comb as calibrator

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Over the past decades, the discovery and characterization of exoplanets has progressed extraordinarily.

In particolar, searches for extrasolar planets using the periodic Doppler shift of stellar spectral lines resulting from the motion of the host star around the barycenter of an exo-solar system, have achieved a precision of ~50 cm/s, sufficient to find Super-Earth-mass planets. However, the detection of Earth-mass planets in the habitable zone around Sun-like stars, will require an order-of-magnitude improvement in RV measurement sensitivity to below 10 cm/s.

Key limitations of RV measurements are extreme precision spectrographs, stable over timescales of years, and ultra-precise and stable wavelength calibration of the astrophysical spectrographs. The astro-frequency comb is becoming the promising candidate for a revolutionary ideal wavelength calibrator providing high density of bright, regularly-spaced optical lines and nearly perfect long-term stability with a improved precision as high as 1 cm/s in astronomical radial velocity measurements.

We present here the results of a series of measurements conducted using the echelle spectrograph FOCES intended to be operated at the 2.0 m Fraunhofer Telescope at the Wendelstein Observatory and an Astro Frequency Comb as calibrator. Different analysis techniques have been applied to investigate the calibration precision and the medium-long term stability of the system in term of changes in stellar radial velocity.

9908-224, Session PS4

Dramatic robustness of a multiple delay dispersed interferometer to spectrograph errors: how mixing delays reduces or cancels wavelength drift

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Externally dispersed interferometry (EDI) with a multiple delays has been used to measure high resolution NIR stellar spectra at the 200 inch Hale telescope having a resolution 6x-10x larger than the native spectrograph (TripleSpec, 950 — 2450 nm). This produced a resolving power of 19,000 from a 2,700 disperser over the full bandwidth of the native spectrograph. Secondly, and the focus of this talk, the robustness of the output high resolution spectrum to lineshape (LSF) drifts and distortions of the native spectrograph was also increased 20x. This is due to the interferometer being crossed with the disperser, so that the former not the latter provides the high frequency information. The amount of observed drifts in TripleSpec native spectrograph was severe and would normally preclude the achieved high resolution. This robustness boost is significant for the community since LSF drifts and distortions are often the limiting factor in achieving m/s scale Doppler radial velocity precisions in astronomical spectrographs. We describe the theoretical basis for the EDI robustness, and the advantages of using multiple rather than single delay. Thirdly, the EDI has demonstrated to also be extremely robust to fixed pattern errors produced by bad detector pixels which pollute the native spectrum. Fourthly, the extremely high dynamic range of EDI has allowed us to measure line height differences between our ThAr lamp and the literature spectrum for weak features (~0.001 height of nearest strong line). Accurate knowledge of a reference spectrum is essential for precision radial velocimetry. Prepared by LLNL under Contract DE-AC52-07NA27344.

9908-225, Session PS4

High-sensitivity, wide coverage, and high-resolution NIR non-cryogenic spectrograph: WINERED

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WINERED is a near-infrared (NIR) high-resolution spectrograph, which is currently mounted on 1.3m Araki telescope of Koyama Astronomical Observatory in Kyoto-Sangyo University, Japan. WINERED is a PI-type instrument,which can be attached to various telescopes with a Nasmyth focus. It covers a wide wavelength range from 0.90 to 1.35μm (z, Y, J-bands) with the spectral resolution of R = 30,000 with 1.5 arcsec slit (for 1.3m telescope with f/10).The main concept of WINERED is to obtain high-resolution infrared spectra of high signal-to-noise and high-quality, which has been achieved with the state-of-the-art optical echelle spectrographs. To realize this concept, WINERED has three distinctive features: (i) optics with no cold stop, (ii) wide spectral coverage, and (iii) high sensitivity. Owing to the first feature, we succeeded in reducing the time for development, alignment, maintenance, and the total cost compared to the usual entirely-cooled NIR spectrographs. Second feature is realized with the spectral coverage of Delta_lambda / lambda ~ 1/6 in a single exposure, which is better than those of all the NIR high-resolution spectrographs attached to 8-10m telescopes (the best number is 1/10 for Subaru/IRCS). This wide coverage is enabled by the combination of decent optical design with cross-dispersed echelle and a large format array (2k x 2k HAWAII2-RG). Third feature makes WINERED as the most sensitive spectrograph among all commissioned/planned NIR high-resolution spectrographs in the world. If attached to 8-10 m telescopes, the limiting magnitudes of WINERED achieving S/N=30 with 1800 sec exposure are expected to be J=19.8 with AO and J=18.0 without AO. Such high sensitivity is achieved by the high-throughput optics (> 0.5) and the very low noise of the system. The major factors of high throughput is the echelle grating and VPH cross-disperser with high diffraction efficiencies of ~0.83 and ~0.86, respectively, and the high Q.E. of HAWAII2-RG (0.83 at 1.23 um). The readout noise of the electronics is 5.3 e- for NDR=32. The ambient thermal background radiation at longer wavelengths than that of WINERED is significantly reduced by two custom-made cold thermal blockers installed in front of the array and also by the short-wavelength cut-off (1.7um) of the array. The thermal background is measured as < 0.02 e-/sec/pix at 273K, which results in the thermal noise less than the typical read noise or the dark noise of the array even with 1800 sec exposure. Since the first-light in 2013, WINERED has been producing fruitful scientific results through a variety of fields from solar system objects, stars, to interstellar medium. The scientific topics include isotope ratios of C and N in comets, a spectral library of stars covering all spectral types and luminosity classes in this relatively uncultivated wavelength range, near-infrared diffuse interstellar bands, and so on. In this paper, we present the summary of design and final performances of WINERED along with the first scientific results. In addition, we briefly introduce a newly-installed high-resolution mode (R~80,000) with a high-blazed echelle grating (refer to Ootsubo et al. in this conference).

9908-226, Session PS4

Thermal stability improvements to the ESPaDOnS spectrograph with the addition of a thermal enclosure

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As part of the GRACES (Gemini Remote Access to CFHT ESPaDOnS Spectrograph) project, a project to link the Gemini-North telescope to the ESPaDOnS (Echelle Polarimetric Device for the Observation of Stars) spectrograph at CFHT (Canada-France-Hawaii Telescope), the original thermal enclosure of the spectrograph needed to be modified. Although the modifications were slight, there was a significant possibility that the thermal stability of ESPaDOnS would be somewhat compromised. To eliminate this risk, a walk-in thermal enclosure was purchased and installed around the ESPaDOnS spectrograph as part of the GRACES project. The thermal impact of these modifications to the ESPaDOnS environment will be analyzed and the effect of the changes on the amplitude and behavior of the spectral drift for the ESPaDOnS and GRACES instruments will be examined.

9908-227, Session PS4

Performance characteristics of two volume phase holographic grisms produced for the ESPRESSO spectrograph

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The ESPRESSO spectrograph requires two volume phase holographic (VPH) grisms as part of its optical design. The two grisms operate as cross-dispersing elements within the spectrographs with each working over a section of the overall spectral range. The grisms are relatively large in size with a working aperture of 185 mm x 185 mm for the blue grism and 215 x 185 mm for the red. This paper describes the specifications of the two grating types, gives the expected theoretical performances of diffraction efficiency for the production designs and presents the actual measured performances of the production grisms.

The blue grism covers the range from 375 nm to 520 nm with a dispersion of 0.88 degrees/nm at the central wavelength. The blue grism operates from 535 nm to 780 nm with a dispersion of 0.47 degrees /nm at 654.8 nm. Both designs use a single input prism to enhance the dispersion of the grism assembly. This paper shows the RCWA theoretical predictions for each of the designs and presents the test data for each of the gratings built.

9908-228, Session PS4

A system to provide sub-milliKelvin temperature control at T~300K for extreme precision optical radial velocimetry

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We present the design and preliminary results for the temperature monitoring and control (TMC) system from our instrument concept for NASA's Extreme Precision Doppler Spectrograph (EPDS). Exquisite temperature control is a requirement for high-precision spectrographs, such as this instrument being designed for the 3.5m WIYN telescope. We demonstrate sub-mk temperature stability over more than a week, and 0.14mK stability over a day in full scale model tests of our EPDS concept, called NEID.

Our TMC system is adapted from that of the Habitable Zone Planet Finder (HPF) instrument, operating temperature 180K. This stability is achieved by enclosing the entire optical train in a high quality (P < 10-7 Torr) vacuum, thereby eliminating convective and molecular heat transport. We have designed and implemented custom electronics—common to HPF and NEID—to measure and control the spectrograph temperature at the sub-mK level.

Our operational concept for NEID involves raising the temperature within the thermal shield to 10-15K above room temperature, and using the ambient environment as a uniform radiative heat sink. The thermal shield is adapted to warm operation with thicker aluminum walls and double the number of heaters, with with even distribution of area served per heater.

We have demonstrated the effectiveness of the NEID temperature control concept via a full-scale warm test of the HPF vacuum chamber. We show that, even when optimized for operation at 180K, the system maintains sub-mK stability at T~300K on the optical bench over more than a week. The ability to measure and control to such high precision unveils a plethora of physical effects that matter at the sub-mK level. We discuss these effects, as well as how they will be further mitigated in the NEID design.

9908-229, Session PS4

Multi-fiber coupling through a miniature lens system into the FOCES spectrograph

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For the future goals of stable long term measurements with the upgraded version of the FOCES at Wendelstein Observatory the light injection into spectrograph was raised to a higher standard. We will present our concept and first results of the light injection consisting of several components namely a 4-fiber slit, the new micro optic system to reimage the light leaving the fiber onto the slit, as well as the new slit mask. The former adjustable slit will be replaced by slit mask glued to the last lens of the micro optic system to further eliminate sources of instabilities.

9908-230, Session PS4

Relative stability of two laser frequency combs for routine operation on HARPS and FOCES

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Astronomical spectrographs have been lacking calibration sources with sufficient precision for the detection of Earth analogues, which requires measuring radial-velocity amplitudes of about 9 cm/s. Laser frequency combs (LFCs) promise to overcome this limitation by offering a regular pattern of spectral lines that is referenced to an atomic clock. We report on the installation and test of an LFC at the two-channel fiber-fed spectrograph HARPS, located at ESO's La Silla Observatory in Chile. The test was conducted in conjunction with a second LFC owned by the University Observatory Munich that was in preparation for its installation at the Wendelstein Observatory as a calibrator for the FOCES spectrograph. This allowed us for the first time to probe the relative stability of two independent astronomical LFCs over an extended wavelength range. Both LFCs covered the spectral range of HARPS to at least 74 % from 460 to 690 nm. After optimization of the light delivery in optical fibers to HARPS to suppress modal noise, a relative stability of the two LFCs in the low cm/s range was obtained. In combination with the data from our four earlier LFC test campaigns on HARPS, the available data now cover a time span of more than six years. This is of great value for judging the long-term stability of an LFC-calibrated spectrograph, the importance of

understanding systematic errors, and the prospects of detecting long-term phenomena such as long-period exoplanets or the acceleration of cosmic objects. After our in-field tests, the LFC for FOCES was transported back to Germany, while the LFC for HARPS remained on the site in preparation for its service as a routine calibration device.

9908-231, Session PS4

CARMENES: the VIS channel spectrograph

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CARMENES (Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Echelle Spectrographs) is a high resolution spectrograph built for the 3.5m telescope at the Calar Alto Observatory (Almeria, Spain), which is operated jointly by the Max-Planck-Society (MPG) and the Spanish National Research Council (CSIC). CARMENES consists of two separated highly stabilized spectrographs covering both the visible (0.55 to 1.0 μm) and the NIR (0.95 to 1.7 μm) wavelength ranges. A spectral resolution of R=82,000 combined with excellent long term stability provide high-accuracy radial-velocity measurements (?1 m/s).

CARMENES has been built by a consortium formed by five German institutions, five Spanish institutions and the Calar Alto Observatory itself. The instrument first light took place on November 2015 and will start operations on January 2016.

An overview of the design and expected performance of the VIS spectrograph system will be given, concentrating on the optical and mechanical design, the realization of the vacuum tank and thermal control to stabilize the spectrograph, and the exposure meter.

The integration phase at Calar Alto Observatory, giving details on the usual issues one is faced if an instrument is first time completely assembled at the observatory and the final implementation of the VIS channel is described as well as the fine tuning performed during the following test and first (technical) commissioning phase. There were - as expected - lessons to be learned.

The technical performance data, especially the achieved resolution, throughput and thermal stability and the resulting radial-velocity accuracy, as measured during the commissioning runs and the first months of science operation of the VIS channel will be shown and compared to the design values.

9908-232, Session PS4

An ultra-stable cryostat for the detectors of ESPRESSO

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ESPRESSO The Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations, is a super-stable Optical High Resolution Spectrograph for the combined coude focus of the VLT. It can be operated by either one of the UTs or collecting the light from up to 4 UTs simultaneously. Given the wide spectral range, the optical path is split into two channels, two large 90 mm x 90 mm CCDs are used to record the full spectrum.

In order to achieve the extremely high stability, ESPRESSO has a fixed optical layout; no moving parts are foreseen inside the spectrograph to maximize the stability and repeatability of the instrument performance and to avoid any thermal load generated inside the spectrograph itself. The optical bench is placed in a vacuum vessel hosted in a three level enclosures system able to guarantee temperature stability of the order of 0.001 K and in a vacuum environment. We aim for a stability of the spectral line on the detector pixel matrix in the order of a few nanometer.

The paper gives a detailed description of the cryostat with the flexible de-coupling of the dewar between the vacuum vessel and optical bench. The design including the measures taken in order to provide an optimal thermal connection and a very accurate mechanical referencing of the large chip. We are going to describe the specific experiment which has been setup in order to verify and physically measure the real stability of the detector “pixels” relative to the rest of the world. We will also present the results obtained with the similar setup measuring the stability of the HARPS detector (the precursor of ESPRESSO) and the preliminary results of the stability of the final ESPRESSO detector system.

9908-233, Session PS4

The Leiden EXoplanet Instrument (LEXI): a high-contrast high-dispersion spectrograph

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The Leiden Exoplanet Instrument (LEXI) will be a new visitor instrument for the William Herschel Telescope. It will be the first instrument specifically designed for high contrast high dispersion spectroscopy at optical wavelengths. The combination of high contrast imaging (HCI) techniques together with the high dispersion spectroscopy (HDS) will be able to reach optical contrast levels of ~10-7. This enables us to characterize young hot gas giants, and uniquely map velocity fields of proto-planetary dust around young stars. LEXI will be a bench-mounted, high dispersion integral field spectrograph that will record spectra on a small area around the star with high spatial resolution and high dynamic range. A prototype is being setup to test the combination of HCI+HDS and its first light is expected in 2016.

9908-234, Session PS4

A calibration unit for the near-infrared spectropolarimeter SPIRou

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SPIRou is a near-infrared spectropolarimeter and high precision radial velocity instrument, to be offered to the CFHT community from 2018. It focuses on two main scientific objectives: (i) the search for Earth-like planets around M dwarfs (especially in their habitable zone) and (ii) the study of stellar and planetary formation in the presence of stellar magnetic field. ?Essential to the short- and long-term precision (1 m/s) are the

calibration and super-stable radial-velocity reference module, fiber linked to the spectrograph.

In this paper, we highlight the main differences in the calibration techniques referring to HARPS@ESO or SOPHIE@OHP: calibration lamps and optics adapted to the Spirou domain (domain 0.98µm-2.35µm), data reduction adapted to the use of a CMOS detector, calibration following star path after telescope and direct to the spectrograph, control of the thermal background contribution.

We also describe the calibration unit architecture, its design and production, including the fluoride fiber links, the Fabry-Perot radial velocity reference unit and the cold source module needed for simultaneous calibration because of K-Band contamination.

9908-235, Session PS4

TARdYS: a high-resolution near-infrared spectrograph for TAO

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TARdYS - the Tao-Aiuc-high-Resolution-Yband Spectrograph - is an instrument concept developed by the Center of Astro Engineering UC and the University of Tokyo for the Tokyo Atacama Observatory - TAO. The observatory will host a 6.5 m IR telescope installed at the summit of Cerro Chanjnantor at an altitude of 5640 m in northern Chile. The instrument being developed and presented here aims at precise RV measurement of M type stars and to give access to a number of additional science cases for the study and monitoring of cool stars. The optical design of the spectrograph is based on a classic white pupil configuration and an R6 echelle grating, which allows to reach relatively high spectral resolution (R > 50,000) with a compact setup. Fibre feeding, simultaneous wavelength calibration and thermal control will guarantee high stability. We present the opto-mechanical design and preliminary results.

9908-236, Session PS4

Advances on FIDEOS the high-resolution spectrograph for the ESO 1m telescope at La Silla

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We present the last advances in the FIDEOS project. FIDEOS is the high resolution spectrograph developed at the Center of Astro Engineering UC for the ESO 1m telescope of La Silla. The spectrograph is based on a classic echelle optical configuration and covers the optical spectral range from 400 to 700 nm with a spectral resolution of about 42,000. Light is fed into the instrument with an optical fibre to guarantee optimal stability. Simultaneous wavelength calibration with a ThAr lamp and thermal control also contribute to make this instrument ideal for precise RV measurement of bright stars.

9908-237, Session PS4

CARMENES: interlocks or the importance of process visualization and system diagnostics in complex astronomical instruments

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With the steadily increasing complexity of scientific instruments, there is an ever-growing demand for improved control electronics. This is especially important in infrared instruments, where the low pressure and challenging cryogenic systems increase the requirements of the overall control system.

CARMENES (Calar Alto high Resolution search for M dwarfs with Exo-earths with a visible and Near-infrared Echelle Spectrograph) is a combination of two spectrographs, one equipped with a CCD for the range 0.55 – 0.95?m, and one with HgCdTe detectors for the range 0.95 –1.7?m. Both spectrographs are coupled to the Calar Alto 3.5 m telescope with optical fibers.

Guiding is performed with a separate camera. Additional fibers are available for simultaneous injection of light from emission line lamps for RV calibration, or, alternatively, from the sky.

The two spectrographs are mounted on benches inside vacuum tanks, which are located in climate controlled chambers inside the air-conditioned coudè laboratory of the 3.5 m dome. Each detector is mounted in a small temperature stabilization system, a Continuous Flow Cryostat which is adapted to the vacuum tank.

That means the control electronics must monitor and adjust many different subsystems in different physical places, mounted at the telescope or placed inside the telescope building, these include:

- The "frontend" mounted at the cassegrain focus of the telescope including the autoguider and the exposuremeter

- The calibration units with the different calibration sources placed in a separate room

- The VIS vacuum tank including the optical bench and the Continuous Flow Cryostat placed inside the temperature chamber build in the coudé room area

- The NIR vacuum tank including the optical bench and the Continuous Flow Cryostat placed inside the temperature chamber build in the coudé room area

- The instrument control electronics and the different pre-vacuum and turbo-molecular pumps in the area between the temperature chambers inside the coudé laboratory

Measurement and control of different physical values like vacuum pressure, temperature, oxygen content, the quality of vacuum, flowrate of cooling

water or voltage and current have to be monitored and controlled by an overall system.

Processes within the vacuum tanks, like evacuation, cooling, warming or flooding with nitrogen gas have to be protected from operator error.

For safety reasons it is essential to have an intelligent Interlock system which will inform the operator in case of malfunction in any part in the instrument. Warnings and Alarms are generated and can even react in autonomous mode starting vacuum pumps and opening or closing valves automatically.

In addition to monitoring safety issues, the process visualization and powerful diagnostic of the Interlock system is able to make all necessary information available in a clear graphical way. This is especially important for the Assembly, Integration and Verification (AIV) phase and to understand the interaction of all sub-systems and see the healthiness and the history of the whole technical instrument processes.

To implement these different demands a comprehensive Interlock system with process visualisation and powerful diagnostics has been developed at the Calar Alto Observatory and the Zentrum für Astronomie Heidelberg (LSW).

9908-238, Session PS4

GIANO and HARPS-N together: towards an Earth-mass detection instrument

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This article describes the works we are doing for modifying the interface between the high resolution infrared spectrograph GIANO (0.97-2.4 micron) and the TNG telescope, passing from a fiber feed configuration to the original design of a direct light-feeding from the telescope to the spectrograph. So doing the IR spectrograph, GIANO, will work in parallel to HARPS-N spectrometer (0.38-0.70 micron), the visible high resolution spectrograph, thanks to a new telescope interface based on a dichroic window that simultaneously feeds the two instrumentes: this is GIARPS (GIAno & haRPS).

The scientific aims of this project are to improve the radial velocity accuracy achievable with GIANO, down to a goal of 1 m/s, the value necessary to detect Earth-mass planets on habitable orbits around late-M stars, to implement simultaneous observations with Harps-N and GIANO optimizing the study of planets around cool stars. The very broad wavelengths range is particularly important to discriminate false radial velocity signals caused by stellar activity. We therefore include several absorption cells with different mixtures of gases and a stabilized Fabry Perot cavity, necessary to have absorption lines over the 0.97–2.4 microns range covered by GIANO.

9908-240, Session PS4

Development of illumination optics in optical scheme of high-resolution fiber-fed echelle-spectrograph for the Big Telescope Alt-azimuth (BTA)

Dmitrii Kukushkin, Dmitrii Sazonenko, Alexey V. Bakholdin, ITMO Univ. (Russian Federation); Gennady G. Valyavin, Special Astrophysical Observatory (Russian Federation)

The report describes the development and optimization of optical scheme of the illumination optics of the entrance slit for the high-resolution fiber-fed echelle-spectrograph. The optical system of the illuminator provides the necessary agreement of the numerical apertures of the fiber and spectrograph, as well as it allows to install the necessary equipment to obtain the required structure of the image.

The entrance slit of the spectrograph is illuminated by a lens illumination system, which forms the image of the output ends of the two optical fibers on the slit of the spectrograph. The operating wavelength region spans from 400 to 750 nm. Since the light beam from the output ends of the optical fibers goes under a certain angle and has a numerical aperture NA=0,22 (F/2.217), it is necessary to convert this beam to the input numerical aperture of the spectrograph NA=0,043 (F/11.6). According to the tasks of the spectrograph in the illuminator we are planning to install a slicer to divide the intermediate image of the fiber cores at the two images forming the output uniformly illuminated rectangular slit. To install the slicer the optical system was designed, with the intermediate image plane (F/30) for placement the slicer in it. The slicer divides each image of output end of the fiber (the core of the fiber) on two parts, arranged one above the other. The structure of the image is the following: all four parts are located one above the other – the two parts form a channel of one optical fiber, two other parts form the other channel, the parts, separated by a dark interval, inside each of the channels should be arranged without considerable gap. Thus, there are the four images at the exit of the illuminator. These images form the entrance slit of the spectrograph. As a result of the designing a five-component, seven-lens illumination system was obtained. The analysis of this optical illumination scheme of the illuminator has shown its efficiency within the entire system of the spectrograph. The main disadvantage of this system is the large number of lenses, affecting the light transmission of the system.

Also we considered the optical system of the illuminator without the slicer. Due to the fact that the slicer is not used in this optical scheme, the system does not require the plane of the intermediate image. This feature has helped to simplify the whole scheme. The obtained system consists of two components and outputs the image of the two cores of optical fibers by performing the necessary conversion of numerical apertures. Because there are fewer lenses in this system, the system has a significantly better transmission in a defined spectral range and lower cost. This illumination system is more technological and simpler to manufacture. However, due to the lack of slicer and the round shape of the image given by the illuminator, the spectral resolution of the spectrograph is lowered.

This research provides a good instrument for performing modern researches for the astronomy.

9908-241, Session PS4

Achieving the resolution of the spectrograph of the 6m Large Azimuthal Telescope

Dmitrii Sazonenko, Dmitrii Kukushkin, Alexey V. Bakholdin, ITMO Univ. (Russian Federation); Gennady G. Valyavin, Special Astrophysical Observatory (Russian Federation)

The basis of any spectral device is the spectral element which disperses the light by wavelength. The spectral resolution requirements for instruments, used for space application, are growing from year to year. Nowadays, the spectral resolution that can give one dispersing element is insufficient. For this reason, modern astronomical spectral instruments use more than one dispersive element. This allows achieving a high spectral resolution with the best distribution of energy over the spectrum.

In the Special Astrophysical Observatory of Russian Academy of Sciences (SAO RAS) creates a spectrograph with a high spectral resolution for 6-meter telescope. The spectrograph consists of a mobile part, located at the focus of the main mirror of the telescope, the stationary part located

under the telescope, and optical fibers, which transmits light from the mobile part to the stationary part. The mobile part provides various operating modes of the spectrograph. The stationary part converts the light to the spectrum for further analysis. The spectral resolution of the stationary part should be R=100000. To achieve such value, the scheme has two spectral elements, with cross-dispersion. The main spectral element is an echelle-grating. This element works in spectral orders from 68 to 127 . The second spectral element is a prism with a diffraction grating on one face. Such an element is called grism. The dispersion of the prism is perpendicular to the dispersion of the echelle-grating. The result is a structure of lines from different spectral orders. Orders are arranged so that the last wavelength of the one order is the first wavelength of the next order. Obtaining such an image on a CCD detector is 4000 by 4000 pixels, with a pixel size of 15 ?m, allows to achieve a spectral resolution of R=100000.

Optical scheme of the spectrograph was designed for operating with the standard echelle-grating. The main task was to design the grism that is to choose the parameters of the grism: optical material, the grism vertex angle, grating frequency. The grism material affects the uniformity of the spectral orders distribution at the detector. It is also an important parameter is the transmittance of the glass over the spectral range of 400-750 nm. Many glasses from different manufacturers were analyzed to choose the optimal variant. The grizm's vertex angle and grating's frequency determine deviation and beam width after the grism. After analyzing all parameters, the optimal grism configuration was found.

An important parameter to achieve the spectral resolution is the size of the slit. The spectral resolution is determined by the width of the slit's image at a certain wavelength. Than the size smaller, the higher resolution can be achieved. To achieve a spectral resolution of 100000, the width of the slit's image at one wavelength should not exceed 2 pixels, i.e. 30 ?m. In this case, the entrance slit width must not exceed 186 ?m. As the entrance slit for the spectrograph is planned to use the actual image of the ends of optical fibers.

9908-242, Session PS4

HARPS3 for a roboticized Isaac Newton telescope

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We present a description of a new instrument development, HARPS3, planned to be installed on an upgraded and roboticized Isaac Newton Telescope by end-2018. HARPS3 will be a high resolution (R ~ 115,000) echelle spectrograph with a wavelength range from 380-690nm. It is being built as part of the Terra Hunting Experiment – a future planned 10 year radial velocity measurement programme to discover Earth-like exoplanets. The instrument design is based on the successful HARPS spectrograph on the 3.6m ESO telescope and HARPS-N on the TNG telescope. The main changes to the design in HARPS3 will be: a customised fibre adapter at the Cassegrain focus providing a stabilised beam feed and on-sky fibre diameter ~ 1.4 arcsec, the implementation of a new continuous flow cryostat to keep the CCD temperature very stable, characterisation of the HARPS3 CCD to map the effective pixel positions and thus provide an improved accuracy wavelength solution, an optimised integrated polarimeter and the instrument integrated into a robotic operation. The robotic operation will optimise our programme which requires our target stars to be measured on a daily basis. We present an overview of the entire project, including a description of our anticipated robotic operation.

9908-243, Session PS4

CARMENES: NIR channel spectrograph, optical, and opto-mechanical as-built design II

María Concepción Cárdenas Vázquez, Santiago Becerril Jarque, Instituto de Astrofísica de Andalucía (Spain); Ernesto Sánchez-Blanco, Instituto de Astrofísica de Andalucía (Spain) and Optical Development (Spain); Pedro J. Amado González, Irene M. Ferro Rodríguez, David Pérez-Medialdea, Instituto de Astrofísica de Andalucía (Spain)

CARMENES is a next-generation radial-velocity instrument. It is the new high resolution high stability spectrograph built for the 3.5m telescope at the Calar Alto Observatory (CAHA, Almería, Spain) by a consortium formed by German and Spanish institutions. This spectrograph is composed by two separated echelle spectrographs, VIS channel (550-1050 nm) and NIR channel (950-1700 nm) at a spectral resolution of R = 82,000. Each channel is fed by two optical fibers from the Cassegrain focus of the telescope, one for the target, and the other for calibration light. Fibers with octagonal cross-section are employed to ensure good stability of the output.

The CARMENES instrument passed its Final Design Review (FDR) in February 2013. The NIR channel has been manufactured, assembled, integrated and verified (MAIV) in the last two years. It was delivered to the observatory in fall 2015, and the commissioning phase on-sky has been accomplished in December 2015. The expected performances comply with the scientific requirements and its science verification started.

This paper covers the NIR channel final as-built optical and opto-mechanical design; from the FDR until make the different subsystems feasible, real and meeting the tolerances. We talk about the different subsystems, the Fiber Exit Unit (which feeds the spectrograph, including the Imager Slicer), the off-axis collimator (used in three bounces), the high dispersion echelle, the cross disperser grism and the 5 lenses camera. The detector is a mosaic of two 2k?2k HAWAII-2RG, giving 4096?2048 pixels with a 2.5 μm cut-off. The optics includes a special cut-off filter for wavelength from 1.7 to 2.5 μm in order to reduce the thermal contribution of that wavelengths range to be within requirements.

The optical design has been optimized for the operation temperature (140 K) but the mechanical design, manufacturing and assembly have been done at room temperature (300 K). The mounts of the optical elements have been designed to ensure survival when temperature changes between 300K and 140K and also to position the elements at the right distances at operation temperature.

The spectrograph is mounted on an optical bench which is housed in

a vacuum tank located in the Coudé laboratory of the 3.5m dome. The instrument works at about 140 K, except for the detector, that works at 82 K. The tank is equipped with a temperature stabilization system capable of keeping the temperature constant to within ± 0.01ºC over 24 hours. The temperature-stabilized environment is necessary to enable a 1 m/s radial velocity precision employing a simultaneous calibration with an emission-line lamp or with a Fabry-Perot etalon.

The MAIV of the channel has been schedule driven since we had with a fixed project deadline. The process of manufacturing and final definition for most of the subsystems have taken place at the same time, and simultaneously with other subsystems being integrated and verified at laboratory, along the complete crazy AIV phase.

9908-244, Session PS4

CARMENES: NIR channel spectrograph, optical AIV plan overview

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The MAIV of the channel has been schedule driven since we had with a fixed project deadline. The process of manufacturing and final definition for most of the subsystems have taken place at the same time, and simultaneously with other subsystems being integrated and verified at laboratory, along the complete crazy AIV phase.

This paper goes through the AIV process and the final laboratory tests.

Concerning the AIV process, we describe how the subsystems have been verified individually before their integration in the spectrograph. When the subsystem is composed by more than one optical element, such as the Fiber Exit Unit (FEU, which feeds the spectrograph, including the Imager Slicer), then the subsystem was aligned at warm and verified at cold as a unit in a testing cryostat, before its integration in the complete instrument. How the system has been aligned at room temperature (300K), taking the off-axis collimator mirror (used in three bounces) of the instrument at the starting point of reference for the complete opto-mechanical alignment. Then we go through the optical path, with the folding mirror alignment, the camera barrel integration and alignment, the echelle grating integration and alignment and the cross disperser grims integration. We also describe how the Exposure Meter, which is feed by the cero order of the echelle, was aligned. Once the optical bench was completely populated and aligned at warm, we applied the calculated off-sets to some elements (FEU, Folding Mirror, EM-FiberExitUnit) in order to have the system aligned at the operation temperature of 140K. Finally we describe the laboratory tests performed along several cryogenic cycles of the complete instrument in order to final adjust and align the complete spectrograph to be within requirements.

We describe how these activities were carried out in order to have the cryogenic channel fully operational and complying with the scientific requirements at the required date. Every subsystem had been in the "critical path" at least one. We had to take some critical and risky technical decisions in order to be on time.

The laboratory final test confirmed the expected NIR channel spectrograph performances, complying with the scientific requirements.

9908-245, Session PS4

CARMENES: NIR channel spectrograph instrument requirements versus performance at telescope

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CARMENES (Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs) is the new high resolution high stability spectrograph built for the 3.5m telescope at the Calar Alto Observatory (CAHA, Almería, Spain) by a consortium formed by German and Spanish institutions and the CAHA observatory itself. This spectrograph is composed by two separated spectrographs, VIS channel (550-1050 nm) and NIR channel (900-1700 nm). The NIR channel has been manufactured, assembled, integrated and verified in the last two years. Operation starts by January 2016.

The NIR channel main difficult lays in the thermo-stabilization of the instrument at cryo-vacuum conditions. An innovative cooling system keeps the spectrograph within the required operation temperature (138.36 K). Therefore, a set of specifications at both system and subsystem levels are stablished. Furthermore, there is an added difficulty: accomplish all requirements in a very short time for this complex instrument (two years for manufacture, integration, acceptance tests and fulfil all requirements).

A complete optical design is optimized not only for room temperature, but also for operation temperature. With this model, the evolution of the optical alignment can be tested in three points during the assembly, verification and integration stage (WARM, WARM-AIV and COLD). In WARM stage, the system is at room temperature. WARM-AIV is the phase where several offsets should be applied at subsystem level in order to correct the aluminium shrinks during cooling down. Finally, the optical model can describe the alignment of the system at operation temperature. On the other hand, the mechanical design, manufacturing and assembly present a temperature of reference for all the dimensions and tolerances of 293 K (20ºC). Mounts, supports and holders of optical elements have been designed to ensure survival when the spectrograph shifts from reference temperature toward NIR channel operation temperature. Note that the detector works at 85K.

This paper shows a comparison between scientific requirements, as-built model of the whole instrument and final performances at telescope. Although, the instrument was delivered to the observatory in fall 2015, and commissioned in December 2015.

The final test on the telescope confirms that the expected NIR channel performances comply with the scientific requirements, and also some improvements are achieved.

9908-246, Session PS4

On-sky Doppler performance of TOU optical very high-resolution spectrograph for detecting low-mass planets

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The TOU robotic, compact very high resolution optical spectrograph (R=100,000, 0.38-0.9 microns) has been fully characterized at the 2 meter Automatic Spectroscopy Telescope (AST) at Fairborn Observatory in Arizona during its pilot survey of 25 bright FGKM dwarfs in 2014-2015. This instrument has delivered sub m/s Doppler precision for bright reference stars with 5-30 min exposures and 0.7 m/s long-term instrument stability, which is the best performance among all of the known Doppler spectrographs to our knowledge. This performance was achieved by maintaining the instrument in a very high vacuum of 1 micron torr and about 0.5 mK (RMS) long-term temperature stability through an innovative close-loop instrument bench temperature control. It has discovered a 21 Earth-mass planet (P=42days) around a bright K dwarf and confirmed three super-Earth planetary systems, HD 1461, 190360 and HD 219314. This instrument will be used to conduct the Dharma Planet Survey (DPS) in 2016-2018 to monitor ~100 nearby very bright FGKM dwarfs (most of them brighter than V=8) at the dedicated 50-inch Robotic Telescope on Mt. Lemmon. With very high RV precision and high cadence (~100 observations per target randomly spread over 450 days), a large number of rocky planets, including possible habitable ones, are expected to be detected. The survey also provides the largest single homogenous high precision RV sample of nearby stars for studying low mass planet populations and constraining various planet formation models. Instrument performance and science results will be presented.

9908-247, Session PS4

Optical design of the NASA-NSF extreme precision Doppler spectrograph concept "wisdom"

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The WISDOM instrument is being developed as part of a NASA-NSF funded study to equip the 3.5m WIYN telescope with an extremely precise radial velocity spectrometer. A general overview of the instrument is presented elsewhere in these proceedings. WISDOM is fed from the telescope using a combination of octagonal and rectangular core fibres, together with an optical double scrambler. The fibre feed includes an ADC and tip-tilt mirror for maximising throughput, as well as a novel pupil slicer. Detailed descriptions of these aspects of the instrument are also presented elsewhere in these proceedings. This paper will concentrate on the spectrograph optical design.

The WISDOM spectrograph is split into "short" (380 to 750nm) and "long" (750 to 1300nm) wavelength channels. Both channels use an asymmetric white pupil optical design, where the echelle gratings and beam sizes are R3.75/125mm and R6/80mm in the short and long channels respectively. Together with the pupil slicer, and octagonal to rectangular fibre coupling, this permits resolving powers over R=110,000 with a 1.2" fibre on the sky. The focal length of the main collimator OAP is 1000mm and the transfer collimator is exactly half this focal length. This greatly reduces the size of the "white pupil" ahead of the cross-dispersers and cameras thereby ensuring a very compact instrument. A dichroic is placed in this collimated beam to split the wavelength coverage again in each channel. The white pupil relay includes a Mangin mirror very close to the intermediate focus which is used to correct the white pupil relay Petzval curvature before it is swept into a cylinder by the cross-dispersers. This mirror, which is a simple off-axis section of a concave/convex singlet lens, is carefully designed in order avoid any potential ghosts. This design decision allows each of the dioptric cameras to be fully optimised and tested independently of the rest of the spectrograph. In each of the final four channels slightly anamorphic VPH grisms are used for cross-dispersion. The orientation and dispersive properties of these gratings have been tuned in order to permit a symmetrical short/long design, to allow the camera optical axes to be exactly parallel to the M1 collimator optical axis, to avoid VPH recombination ghosts, and also to ensure that the quasi-Littrow slit tilt can be removed by rotating the slit. This arrangement also allows the four channel instrument to fit inside a single vacuum tank approximately 850mm in diameter and around 1.8m in length. The spectral footprints cover 4k x 4k and 6k x 6k CCDs with 15um pixels in the short "blue" and "green" wavelength channels respectively. All-spherical dioptric cameras with 425mm focal lengths give 3.5 pixel sampling of a 120k resolution element. A 4k x 4k CCD with 15um pixels is used in the long "red" channel, with a HgCdTe 1.7um cutoff 4k x 4k detector with 10um pixels is to be used in the long "NIR" channel. Again, in each case the focal lengths (258 and 172mm) of the dioptric cameras ensure 3.5 pixel sampling of the same 120k resolution element. The baseline design for the cameras ensures that the highest possible (near diffraction limited) image quality is achieved across all wavelengths, while also ensuring insensitivity of spot centroids to any variation in the pupil illumination. Fully ray-traced simulations of the spectral formats are used to demonstrate the optical performance, as well as to provide pre- first-light spectra that can be used for optimisation of the data reduction.

9908-248, Session PS4

Performance and future developments of the RHEA single-mode spectrograph

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The Replicable High-resolution Exoplanet and Asteroseismology (RHEA) spectrograph is being developed to serve as a basis for multiple copies across a network of small robotic telescopes. The spectrograph operates at the diffraction-limit by using a single-mode fiber input, resulting in a compact and modal-noise-free unit. The optical design is mainly based on off-the-shelf available components and comprises a near-Littrow configuration with prism cross-disperser. The echelle format covers a wavelength range of 430-650 nm at R~75,000 spectral resolution. In this paper we briefly summarize the current status of the instrument and present preliminary results from the first on-sky demonstration of the prototype using a fully automated 0.4 m telescope, where we observe stable and semi-variable stars up to V=3.5 magnitude. Future steps to enhance the efficiency and passive stability of RHEA are discussed in detail. For example, we show the concept of using a multi-fiber injection unit (e.g. Photonic Lantern) which not only enables increased throughput but also offers simultaneous wavelength calibration. To further improve the intrinsic precision we outline a cost-effective way of housing the complete instrument in a vacuum chamber. This will eliminate residual low amplitude temperature and pressure oscillations over long time scales, necessary to perform long-baseline precision RV observations.

9908-249, Session PS4

A new fiber link for the HERMES spectrograph: throughput, scrambling, and modal noise issues

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HERMES, a fiber-fed high-resolution spectrograph, is the workhorse instrument of the Mercator Telescope at the Roque De Los Muchachos Observatory on La Palma (Spain). It is in operation since 2009 and producing very satisfying results. To further improve the spectrograph performance, we are now planning to upgrade the fiber link. This upgrade targets several goals: improved scrambling through the use of an octagonal fiber, reduction of fiber modal noise to enable very high signal-to-noise spectroscopy, increasing the fiber link throughput, and finally, the addition of a simultaneous wavelength reference spectrum to the high-resolution mode of the spectrograph in order to achieve an increased radial velocity accuracy. The high-resolution mode of HERMES makes use of a double-image image slicer, leading to a wide cross-order profile. As a consequence, the inter-order space that is available for interlacing a reference spectrum with the spectrum of the science target, is extremely limited. For this reason, we have to limit the diameter of the wavelength reference fiber to only 25 micron. Such a narrow fiber introduces the same type of modal noise problems in the optical domain as faced by the new generation of radial velocity spectrographs operating in the near-infrared spectral range. In this contribution we discuss the design of the new fiber link, paying special attention to the issue of modal noise mitigation. We also present the results of laboratory measurements of focal-ratio-degradation and scrambling performance of the new 72-micron octagonal science fiber, and compare this with the performance of the original 80-micron circular fiber.

9908-251, Session PS4

NEWS: the near-infrared Echelle for wideband spectroscopy

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We present an updated optical and mechanical design of NEWS: the Near-infrared Echelle for Wide-band Spectroscopy (formerly called HiJaK: the High-resolution J, H and K spectrometer), a compact, high-resolution, near-infrared spectrometer for 5-meter class telescopes. NEWS achieves a resolution of 60,000 over 0.8-2.5 microns via a high blaze angle, R6 echelle grating with coarsely spaced rulings. The coarse ruling reduces the free spectral range of the orders, allowing them to be well sampled by a detector with only 2048 pixels in the dispersion direction. With a 0.5 arcsecond by 5 arcsecond slit, the full 0.8-2.5 micron range can be acquired in 5 modes via a filter wheel to select different orders of the cross-dispersing grating.

A single parabolic mirror, used off-axis, collimates the 4 cm beam onto both the echelle and cross-dispersing gratings. The echelle is tilted 1.5 degrees out-of-plane to separate the dispersed beam from the incoming beam at the intermediate image plane. To reduce aberrations introduced by dispersing onto the collimator, NEWS employs a Mangin fold mirror consisting of a CaF2 lens with a reflective coating on one surface. The fold mirror redirects the beam to the opposite side of the parabolic mirror for collimation onto the cross-disperser. An 8-element, all-spherical camera images the spectrum onto a 2048x2048 pixel detector and achieves RMS spot sizes smaller than the 18 micron pixel size.

NEWS has been designed to mount to the instrument cube at the Cassegrain focus of the the new 4.3-meter Discovery Channel Telescope in Happy Jack, Arizona. To meet the strict weight and size requirements for mounting to the Cassegrain, we designed NEWS to be highly space-efficient without sacrificing performance or capability. All optics mount to a honey-combed and light-weighted optical bench to be milled from a single piece of aluminium. The instrument is designed to fit within a 100x65x30 cm volume and weigh less than 200 kg.

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Commissioning the dual etalon Fabry-Perot modes of the Robert Stobie spectrograph on the Southern African Large Telescope

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The Robert Stobie Spectrograph (RSS) is the prime focus main workhorse instrument on the Southern African Large Telescope (SALT). It was designed to have a wide range of capabilities and observing modes, each one rapidly reconfigurable under software control: imaging, long-slit spectroscopy, multi-object spectroscopy, Fabry-Pérot imaging spectroscopy, and polarimetry in combination with any of the other modes. The SALT RSS Fabry-Pérot system provides spectroscopic imaging over the entire 8 arcminute diameter RSS science field of view, in the wavelength range 430-860 nm, with spectral resolutions ranging from 300 to10,000.

The system consists of three etalons with gap spacings of ~0.6 nm, ~2.8 nm, and ~13.6 nm, referred to as the low resolution (LR), medium resolution (MR), and high resolution (HR) etalons, respectively. The gap and parallelism of the etalons are adjusted with piezoelectric spacers, and are measured with capacitive sensors in a servo control system. The range of gap spacing of the LR etalon is sufficient to provide two spectral resolution modes, low resolution (LR) and tunable filter (TF), with spectral resolution 600 and 300, respectively. The desired interference order of the LR etalon is selected with one of 40 interference filters. In order to limit the number of order-selecting filters required, the MR and HR etalons are designed to be used in conjunction with the LR etalon in dual-etalon configuration (also including one of the interference filters).

During commissioning of the dual etalon modes, a serious reflection problem between the two etalons was discovered. Multiple reflections between the etalons introduce a series of strong ghost images, significantly degrading image quality and precluding useful observations. Flexure in the original etalon mountings made it impossible to keep the etalons aligned sufficiently well to eliminate these ghosts. The MR etalon has been successfully used in single etalon mode since 2012 (but with three adjacent interference orders transmitted), but single etalon mode is not feasible for the HR etalon with the existing filters.

An improved mounting design for the etalons that provides the necessary mechanical robustness was implemented in 2015. Temporal drifts in parallelism of each etalon also introduce misalignments, requiring an efficient way of optimizing the parallelism on a nightly basis. The new dual etalon system was commissioned in late 2015 and is now producing useful scientific observations.

In this paper, we present the details of the improved mechanical design, a new method for rapidly measuring and adjusting etalon parallelism in-situ, a way to use dual etalon measurements to determine the transmission of the individual etalons, other lessons learned from the implementation of dual etalon mode, and the first science verification results.

9908-253, Session PS4

A high-resolution spectrograph for the 72cm Waltz Telescope at Landessternwarte, Heidelberg

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The Waltz Spectrograph is a fibre-fed bench-mounted high-resolution cross-dispersed echelle spectrograph for the 72 cm Waltz telescope at the Landessternwarte, Heidelberg. It is based on an 31.6 lines/mm 63.5° blaze angle echelle grating in white-pupil configuration, providing a spectral resolution of R ~ 66,000 covering the spectral range between 420nm-750nm in one single CCD exposure. An equilateral prism is used for cross-dispersing the echelle orders. The spectrum is focused by an F/5 apochromat objective camera with 530mm of focal length , onto a 2k x 2k array detector with 13.5 um per pixel. The spectrograph will be fed by one rectangular fibre with 25 um x 100 um size, providing a 2.6 pix spectral sampling on the detector centre. An exposure meter will be included into the spectrograph, to provide a precise photon-weighted midpoint of the exposure, to be used as the time for which the barycentric correction is computed.

An iodine cell will be used for wavelength calibration for high precision radial velocities. In addition, a ThAr lamp can be used when not working in the high precision RV regime.

The Waltz spectrograph instrument consist on three different modules: the telescope front-end, the calibration unit and the spectrograph. The telescope will be connected to the spectrograph via the front end module which allows us to feed the instrument with starlight, inject the light from the calibration unit to the spectrograph and place in and out the I2 cell on the telescope optical axis. A Bowen-Walraven image slicer will be placed at the focal plane of the telescope, to reformat the image of the star into a slit, to couple efficiently the light of the star into the rectangular fibre. The fibre will be fed with an input beam of F/5.5, to minimize focal ratio degradation.

The instrument will be used both for student education as well as for science. The main scientific project is the continuation of our Doppler survey of K-giants which had been carried out at Lick Observatory from 1999 to 2011. The giant stars are all rather bright (V < 6), so that it should be possible to achieve S/N of about 100 in half an hour integration.

Our goal is to reach a radial velocity precision of 5 m/s, providing an instrument for exoplanetary Doppler detection. We describe the design and first results of the spectrograph. Commissioning of the Waltz spectrograph is scheduled for 2016.

9908-254, Session PS4

A comprehensive radial velocity error budget for next generation Doppler spectrometers

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We present a comprehensive and rigorous radial velocity (RV) error budget for the next generation Extreme Precision Doppler Spectrometer (EPDS) on the 3.5-meter WIYN telescope. This RV error budget is largely based on the systems engineering approach of Podgorski et al. (2014), though includes many additional error sources for WIYN/EPDS. We consider RV error contributions from the EPDS spectrometer optomechanics, instrument environment, wavelength calibration sources, detector effects, telescope illumination, fiber injection system, data reduction pipelines, telluric contamination, and atmospheric variations. Many of these error terms are traced by the instrument calibration fiber, while others are not. We separate error sources that are 'calibratable', and combine these in quadrature with contributions from 'uncalibratable' terms assuming reasonable levels of calibration accuracy. For each term, we justify the RV magnitude with detailed physical models or reasonable estimations to derive a single expected instrumental error estimate. This comprehensive error analysis is not only essential for achieving a desired measurement precision, but also to identify the technological path towards 10 cm/s precision.

9908-255, Session PS4

Espresso APSU integration and performance verification

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ESPRESSO is a new generation spectrograph for ESO's Very Large Telescope, whose purpose is to search for rocky extrasolar planets and determine possible variability of physical constants. This paper describes the functionalities of the Anamorphic Pupil Slicer Unit (APSU), one of the most critical optomechanical system of the ESPRESSO instrument. The key component - the slicer - is used to increase the resolving power by decreasing the slit width, based on simplified optical component that introduces large anamorphism while keeping low aberrations. At the focal plane, 12 miniprisms are necessary to differently fold each field to correctly illuminate the echelle. The positioning process of these crucial devices has been defined and tested, including the glue injection control mechanism. It is described the metrology procedure adopted, starting from CMM measurements of each single component, the alignment technique and the testing activities for the whole assembly.

9908-256, Session PS4

Precision velocimetry planet hunting with PARAS: current performance and lessons to inform future extreme precision radial velocity instruments

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The PRL Advanced Radial-velocity Abu-sky Search (PARAS) instrument is a fiber-fed stabilized high-resolution cross-dispersed echelle spectrograph, located on the 1.2m telescope in Mt. Abu India. Designed for exoplanet detection, PARAS is capable of single-shot spectral coverage of 3800–9500 Å, and currently achieving radial velocity (RV) precisions approaching ~1m/s over several months using simultaneous ThAr calibration. As such, it is one of the few dedicated stabilized fiber-fed spectrographs on small (1-2) telescopes that are able to fill an important niche in RV follow-up and stellar characterization. The success of ground-based RV surveys is also motivating the push into extreme precisions, with goals of ~10cm/s in the optical and <1m/s in the near-infrared. Lessons from existing instruments like PARAS are invaluable in informing hardware design, providing pipeline prototypes, and guiding scientific surveys. Here we present our current precision estimates of PARAS based on observations of bright RV standard stars, and describe the evolution of the data reduction and RV analysis pipeline as we gather longer baselines of data and instrument characterization progresses. Secondly, we discuss how our experience with PARAS is a critical component in the development of future cutting edge instruments like (1) the Habitable Zone Planet Finder (HPF), a near-infrared spectrograph optimized to look for planets around M dwarfs, scheduled to be commissioned on the Hobby Eberly Telescope in Fall 2016, and (2) the NEID optical spectrograph, designed in response to NASA's call for an extreme precision Doppler spectrometer (EPDS) for the WIYN telescope. In anticipation of instruments like TESS and GAIA, the ground-based RV support system is being reinforced. We emphasize that instruments like PARAS will play an intrinsic role in providing both complementary follow-up and battlefront experience for these next generation of precision velocimeters.

9908-257, Session PS4

CARMENES: NIR channel spectrograph, optical AIV main challenges and highlights

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CARMENES is the new high resolution high stability spectrograph built for the 3.5m telescope at the Calar Alto Observatory (CAHA, Almeria, Spain) by a consortium formed by German and Spanish institutions. This spectrograph is composed by two separated spectrographs, VIS channel (550-1050 nm) and NIR channel (900-1700 nm), wavelengths ranges with spectral resolution of R=82,000. The NIR channel has been manufactured, assembled, integrated and verified in the last two years. It was delivered to the observatory in fall 2015, and commissioned in December 2015. The expected performances comply with the scientific requirements and its science verification started.

In this paper is the main challenges and highlights during the optical assembly, verification and integration (AIV) stage are shown.

The main challenge at system level is the alignment of several subsystems which shift during the cooling-down towards the operation temperature (138.36 K) because the aluminum optical bench shrinks. To solve this problem there are established three reference systems. WARM, WARM-AIV and COLD. In WARM, i.e. at room temperature, all the subsystem should be well aligned. In WARM-AIV, an offset should be applied to almost all the subsystems. Those offset will correct the aluminum shrinking when the instrument is cooling-down towards the COLD stage. The well alignment depends on these values.

For a complete system test, several cryo-vacuum cycles (CVCs) are carried out. Due to timing issues, the number of cycles was reduced. This implies risky decisions like align at WARM stage, applied offsets (WARM-AIV) and check the system at COLD stage with science detector.

The subsystems which integrate the main optical layout are: Fiber Exit Unit (FEU), collimator (off-Axis parabolic mirror), Echèlle grating, folding mirror (FM), cross-disperser (CD) and camera barrel (CB). In addition, there is an extra subsystem, called Exposure Meter (EM), in charge of photon counting.

The collimator is the reference system of the opto-mechanical alignment; therefore, its positioning is quite delicate. The FEU output is the system optical object. So this is the most critical subsystem. Before FEU integration, it was tested under cryo-vacuum conditions. For that purpose, a complex set-up was created. The Echèlle grating structure determines the efficiency peak. When the spectrograph is cooling down, this structure is slightly affected shifting this efficiency peak. To correct it a fine tuning is required using image analysis.

For a fine position of the spectrum over the detector, the CB should be adjusted carefully. On the other hand the detector should reach the optimum focus in tilt and position. The checkup consists in the analysis of the full width half maximum (FWHM) of lines at flat field images in the spatial direction. The lower the FWHM, the better focus position along the complete focal plane.

EM measures the flux coming from the science light. The main challenge of the EM AIV was the optical alignment. The need for large offsets to compensate the aluminum shrink adds a new complexity for the alignment. Measuring the flux during the cooling-down gives information about how stable the alignment is.

9908-258, Session PS4

EXPRES: a next generation RV spectrograph in the search for earth-like worlds

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The EXtreme PREcision Spectrograph (EXPRES) is an optical fiber fed echelle being designed and built at the Yale Exoplanet Laboratory to be installed on the 4.3 meter Discovery Channel Telescope operated by Lowell Observatory. The primary science driver for EXPRES is to detect Earth-like worlds around Sun-like stars. With this in mind, we are designing the spectrograph to have an instrumental precision of 0.1 m/s so that the on-sky measurement precision (that includes modeling for RV noise from the star) can reach at least 0.5 m/s. This goal places challenging requirements on every aspect of the instrument development, including optomechanical design, environmental control, image stabilization, fiber coupling, and wavelength calibration. In this paper we describe our detailed error budget, our preliminary design for the instrument, and the use of integrated structural, thermal, and optical analysis (STOP) to verify the system requirements can be met.

There are three optomechanical subsystems that make up EXPRES; the front-end module, spectrograph, and wavelength calibration unit. The three subsystems operate from 380 to 680 nm, and are connected via optical fibers. The front-end interfaces to an instrument cube at the telescope Cassegrain focus. It provides atmospheric dispersion compensation down to a Zenith angle of 65 degrees, fast tip-tilt guiding using a high-speed EMCCD camera, reimaging optics for injection into an octagonal science fiber, and interface optics to inject calibration light into the science fiber. The science fiber then transports the telescope light from the front-end module to a climate controlled room that houses the spectrograph and wavelength calibration unit. Prior to entering the spectrograph, the science fiber is sliced to achieve higher resolution and double scrambled to mitigate modal noise. The slicer converts the octagonal fiber into a 1 x

4 rectangular fiber which serves as the "entrance slit" to the spectrograph. The spectrograph is an asymmetric white-pupil design with a resolution of 150,000. The wavelength calibration unit can inject light from a laser frequency comb, Th-Ar lamp, or quartz lamp, either directly into the spectrograph, or out into the front-end for injection into the science fiber.

EXPRES is funded by the National Science Foundation Major Research Instrumentation Program.

9908-259, Session PS4

CARMENES-NIR channel spectrograph: optical and opto-mechanical as-built design I

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CARMENES is the new high-resolution high-stability spectrograph built for the 3.5m telescope at the Calar Alto Observatory (CAHA, Almería, Spain) by a consortium formed by German and Spanish institutions. This instrument is composed by two separated spectrographs: VIS channel (550-1050 nm) and NIR channel (900-1700 nm). The NIR-channel spectrograph's responsible is the Instituto de Astrofísica de Andalucía, IAA-CSIC. The channel has been manufactured, assembled, integrated and verified in the last two years. It was delivered to the observatory in fall 2015, and commissioned in December 2015. The expected performances comply with the scientific requirements and its science verification started.

This paper covers the NIR channel final as-built design of the piece of mechanics affecting the opto-mechanical and structural behavior of the optics included in the NIR-channel. This includes of course all the opto-mechanical mounts and the bench where all of them are attached to.

All the mechanics here involved has been thought to behave extremely stable. Indeed, the overall stability of the CARMENEs-NIR spectrograph is one the factor to achieve high radial-velocity accuracy, the mechanical stability being one important contribution to it. This notion of stability has driven the main design guidelines leading to low-stress components compliant with the temperature travel required to reach working conditions (138K) from ambient conditions.

Special role has played in the present design kinematic and quasi-kinematic mounts, as well as other ways to decouple effects coming from the dimensional shrinkage due to the temperature travel. Additionally, this notion to maximize mechanical stability has led us to include additional, customized ageing treatments for all the mechanical components involved.

In particular, the present work describes the final design of the following subsystems. The FEU (Fiber Exit Unit) delivers the light to the spectrograph by means of two fibers as well as accommodate the #f and implement the slicing of the beams. Next, the Collimator mirror Mount, this being the most massive element, receives the beam from the FEU and redirects to the Échelle Mount, one of the biggest component of its class worldwide, which is in charge of providing the long dispersion of the light. After that, the beam goes again to the Collimator being redirected to a narrow Folding Mirror, which, in turn, returns the beam to the Collimator (3rd pass). Finally the beam takes its collimating path to the Cross Disperser and the Camera Barrel behind, just before to come into the Detector Cryostat.

In addition, two more opto-mechanical mounts are described as they belong to the Exposure Meter, which is an additional subsystem in charge of providing the exposure mean reference according to the photon count measured. Finally, the optical bench plays a key role to not even slightly stress the opto-mechanical mounts and decouple them from any undesired effect outside.

9908-260, Session PS4

Demonstrated precision environmental control techniques: a blueprint for a broad range of precision RV instruments

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A principal requirement for a precision Doppler instrument is thermal and opto-mechanical stability of the full optical train. It is now standard practice to fiber-feed these instruments and to enclose the optics in a vacuum chamber. While vacuum environments eliminate convection and minimize coupling to the ambient environment, thermal stability remains the primary cause of environmentally induced RV errors. Through novel enhancements of control techniques originally developed for cryogenic instruments like HPF, we have demonstrated exquisite thermal (< 1milliKelvin) and vacuum (<1.d-7 Torr) stability – essentially eliminating environmentally induced RV errors. This report describes the basic concept and implementation of this technique, and enables broad applicability to a range of precision RV instruments.

9908-261, Session PS4

The VLT/CRIRES+ calibration unit: design, integration, and test results including a novel Fabry-Perot etalon for wavelength calibration from 1-5um

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The VLT/CRIRES+ instrument will be the premier high-resolution, infra-red spectrograph at ESO's Very Large Telescope in early 2018. The ambitious instrument upgrade project has recently entered its assembly and integration phase, implementing a set of new capabilities such as cross-dispersion, a new detector system, spectro-polarimetry, and a set of newly developed, tailored wavelength calibration sources.

In this paper, we discuss the design of the complete calibration unit, and describe the strategy and its implementation featuring high-precision infra-red absorption gas-cells for RV studies, a next-generation Uranium-Neon emission lamp, an enhanced metrology system for long-term instrumental stability, and the workhorse wavelength calibration tool: a broad-band infra-red Fabry-Perot etalon system. The stabilized etalon unit is a new challenging addition to CRIRES+ and serves as the new precision calibrator in all modes, including the spectro-polarimeter. Its optical design and the challenges to overcome are detailed, and we also present first results of the prototype etalon system on CRIRES and demonstrate its performance.

9908-262, Session PS4

NRES: the network of robotic Echelle spectrographs

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Las Cumbres Observatory Global Network (LCOGT) is building the Network of Robotic Echelle Spectrographs (NRES), which will consist of six identical, optical (390 - 860 nm) high-precision spectrographs, each fiber-fed simultaneously by up to two 1-meter telescopes and a thorium argon calibration source. We plan to install one at up to 6 observatory sites in the Northern and Southern hemispheres, creating a single, globally-distributed, autonomous spectrograph facility using up to twelve 1-m telescopes. Simulations suggest we will achieve long-term radial velocity precision of 3 m/s in less than an hour for stars brighter than V = 12. We have been funded with NSF MRI and ATI grants, and expect our first spectrograph to be deployed in mid 2016, with the full network operation of 5 or 6 units beginning in 2017. We will briefly overview the NRES design, goals, robotic operation, and status. In addition, we will discuss early results from our prototype spectrograph, the laboratory and on-sky performance of our first production unit, and the ongoing software development effort to bring this resource online.

9908-263, Session PS4

PFES2: new primary focus Echelle spectrograph for Russian 6-m telescope

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In the primary focus of the Russian 6-m telescope large dimention spectrographs can be installed (up to 160 sm). In late 90-es we crated the echelle spectrograph PFES with collimated beam of 50 mm for moderate spectral resolution (R=15000) spectroscopy as well as for stellar spectropolarimetry. We used small CCD so observations in blue and red optical sub-regions can be obtained by using changed cross-dispertion difraction gratins. Now we are presenting the new optical design of the new instrument PFES2 for faint stellar spectroscopy and spectropolarimetry. Parameters are: linse collimator 1:4; collimated beam diameter d=70 mm, echelle grove density is 37.5 grv/mm; camera 1:1.8 with focus F=200 mm ; detector 2??2?. In contrast to PFES optical layout (mirror collimator - echelle- cross disperse grating - linse camera) we propose prism+grating cross dispertion unit for PFES2 that allows to observe in one of two wavelength regions: 380-810 nm or 440-1000 nm. For slit of 0.5 arcsec spectral resolution is about R=30000. Observations can be obtained in spectropolatimetric mode in all 4 Stocks parameters with spectral resolution about R=21000. PFES2 instrument is now at assambly stage.

9908-264, Session PS4

Spectrograph sensitivity analysis: an efficient tool for different design phases

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In this paper we present an efficient tool developed to perform opto-mechanical tolerance and sensitivity analysis both for the preliminary and final design phases of a spectrograph. With this tool it will be possible to evaluate the effect of mechanical perturbation of each single spectrograph optical element in terms of image stability, i.e the motion of the echellogram on the spectrograph focal plane, and of image quality, i.e. the spot size of the different echellogram wavelengths. We present the Matlab-Zemax script architecture of the tool. In addition we present the detailed results concerning its application to the sensitivity analysis of the ESPRESSO spectrograph (the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations which will be soon installed on ESO's Very Large Telescope) in the framework of the incoming assembly, alignment and integration phases.

9908-265, Session PS4

SHREK: stable high-resolution Echelle for Keck

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SHREK is a fiber-fed, high-resolution, high-stability spectrometer in development at the UC Berkeley Space Sciences Laboratory for the W.M. Keck Observatory. The instrument will be used to characterize exoplanets via Doppler spectroscopy with a single measurement precision of 0.5 m/s or better. SHREK will have a 200mm collimated beam diameter and a resolving power of >80,000. The design includes a green channel (440nm to 590nm) and red channel (590nm to 850nm). A novel design aspect of SHREK is the use of a Zerodur optical bench, and Zerodur optics with integral mounts, to provide stability against thermal expansion and contraction effects.

9908-266, Session PS4

Ultra-stable temperature and pressure control for the Habitable-zone Planet Finder spectrograph

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States); Basil Blank, PulseRay (United States)

We present the design and the long-term stability results of the Environmental Control System (ECS) for the Habitable Zone Planet Finder (HPF), a near infrared (NIR) ultra-stable spectrograph for the 10m class Hobby-Eberly Telescope. Exquisite temperature and pressure stability is required for high precision (<1m/s) radial velocity spectrographs, as temperature and pressure variations inside the instrument can easily induce systematic Doppler drifts of several tens to hundreds of meters per second.

The HPF ECS minimizes these errors by enclosing the full optical train in a thermally stabilized high-vacuum environment (<10-7 Torr), eliminating convective heat transport. This ensures the optics are only coupled to the surroundings via radiation. High efficiency Multi-Layer Insulation blankets, and a passive external thermal enclosure further isolate the optics from ambient perturbations. An actively controlled radiation shield, outfitted with high-fidelity custom feedback electronics, compensates for the dampened temperature fluctuations. The radiation shield is maintained at a 180K operating temperature, motivated by the choice of a Teledyne Hawaii-2RG NIR detector with a 1.7micron cutoff. A large internal LN2 tank acts as a heat sink for the detector array and radiation shield. Long-term high-quality vacuum is achieved with activated charcoal getters directly mounted to the LN2 tank and a commercially available NEXTorr pump from SAES getters.

This environmental control approach is simple, robust, and easily adaptable to stabilize large-scale instruments at the sub-mK level for a wide range of operating temperatures. Preliminary tests of the HPF ECS system at room temperature have already demonstrated sub-mK stability over more than one week. Here we present the latest stability results from full-scale operation at 180K.

9908-267, Session PS4

Integration of the multi mini prism device for the ESPRESSO APSU

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ESPRESSO is a new generation spectrograph for ESO's Very Large Telescope, whose purpose is to search for rocky extrasolar planets and determine possible variability of physical constants. At the spectrograph focal plane, 12 miniprisms are necessary to differently fold each field to correctly illuminate the echelle. This paper describes the procedure used to assembly the multiminiprism system, monitoring the critical aspects such us the definition of the xy zero, the parallelism of the gluing interfaces and the control of the glue thickness.

9908-268, Session PS4

The iLocater cryostat: design and thermal control strategy for precision radial velocity measurements

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The current generation of precision radial velocity (RV) instrument are seeing-limited in design. In order to achieve high spectral resolution on 8m class telescopes, instruments require large optics and in turn, large instrument volumes. Achieving milli-Kelvin thermal stability for these systems is challenging but is vital to achieve a single measurement RV precision of better than 1m/s. This precision is crucial in the search for Earth-like exoplanets.

iLocater, a next generation RV instrument being developed for the Large Binocular Telescope (LBT), uses the LBT adaptive optics (AO) system to inject a diffraction-limited beam into single-mode fibers. These fibers illuminate the instrument spectrograph, facilitating a diffraction-limited design and a significantly smaller instrument volume compared to instruments today. This enables intrinsic instrument stability and precision thermal control.

We present the current design of the iLocater cryostat which houses the instrument spectrograph. The spectrograph is situated within two radiation shields inside the MLI lined instrument vacuum chamber. The outer shield is actively controlled to maintain instrument stability and minimize the effects of thermal changes from the external environment.

The instrument is cooled to an operating temperature of 60K using two pulse-tube cryocoolers from Cryomech which are vibrationally isolated from the internal vacuum structure. To improve the intrinsic stability of the instrument, the optical board and mounts for the spectrograph optics are made from Invar which offers a CTE value an order of magnitude better than aluminum. Combined, the small footprint of the instrument spectrograph, the use of Invar and a precision thermal control strategy will allow long-term milli-Kelvin stability of the instrument to be achieved.

9908-269, Session PS4

CRIGGLEX: a novel long-path infrared gas-absorption cell for VLT/CRIRES+

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We present the design of a newly developed gas-absorption cell with very long optical path-length for precision wavelength calibration. The CRIGGLEX project is an ambitious effort to extend the absorption-cell technique to the infra-red wavelength regime and enable high-precision IR radial velocity experiments in regimes where traditional short-path cells are no longer feasible, and on spectrographs with extreme space limitations in the optical train. Our purely reflective optical design allows for an active path-length of over 3m in the spectroscopic reference medium, while at the same time only a small pick-off unit is inserted into the telescope beam in front of the spectrograph. The design is flexible to adapt to a range of telescope/instrument requirements, and is particularly optimised for the upcoming CRIRES+ spectrograph at the VLT, supporting the full instrumental field of view and the adaptive optics capabilities, while maintaining the telescope beam properties.

We discuss the optical design, the mechanical implementation, and demonstrate the system performance of a fully integrated prototype unit, including the challenges and lessons learnt on the system's complex opto-mechanical alignment.

9908-270, Session PS4

VINROUGE: a very compact 2-5um high-resolution spectrograph with germanium immersion grating

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The 2-5 um wavelength region is an essential window to access to the molecules of astrophysical interest through their stretching vibration transitions (e.g., C-H, N-H, O-H, C-O, and C-N) even for symmetric molecules (e.g., H3+ and CH3+ which have never been detected in the radio region because of zero permanent electric dipole moment). The ro-vibrational spectra of those molecules are diagnostic not only for chemical abundance but also for temperature, number density and kinetics of the gas in the relatively low-temperature environments like molecular clouds, proto-planetary disks, circumstellar envelopes and low-temperature stars. The high-resolution spectroscopy which simultaneously covers is necessary to resolve the rotational structure of vibrational spectrum for the various molecular species.

VINROUGE is a high-efficiency and high-resolution spectrograph to study these astronomical molecules in K, L, and M bands. This instrument is being developed by Laboratory of Infrared High-resolution spectroscopy (LiH) of Koyama Astronomical Observatory in Kyoto Sangyo University, Japan. VINROUGE is designed to be compact (600mmL x 600mmW x 500mmH) despite the high resolution (R = 80,000) by making use of an Germainium (n = 4) immersion grating, so that it can be flexibly installed at the Cassegrain focus of any 3-8 m telescopes.

VINROUGE employs a white pupil type echelle spectrograph that can reduces the beam size, resulting in the small size of the instrument. The total throughput of VINROUGE reaches greater than 25%, which is achieved by the combination of optical elements with high throughput: specially-designed immersion grating and cross-dispersers, an optics consisting of reflective mirrors, and a large format and high Q.E. infrared array. The immersion grating is designed to have the blaze angle of 75 degree, the groove pitch of 57.1 um, and the apex angle of 86 degree. The apex angle smaller than the right angle and the Au reflective coating on the grating surface maximize the diffraction efficiency up to 70% (see Sarugaku et al. in this conference). VINROUGE uses four reflective gratings as cross-disperser (one is for K-band, two are for L-band, and one is for M-band), for which diffraction efficiencies are optimized for each band. All optics of VINROUGE (the collimator, the relay, and the camera) are reflective optics with high-reflective Au or Ag coating in IR, based on three mirror anastigmat (TMA) configuration. We adapt the 5.3 um cutoff HWAII-2RG as the detector, which shows the Q.E. of > 80%. The optics is athermal with all the optics including reflective mirrors, mirror holders and optical bench are made of the same extremely-low expansion material, SiC or Cordierite, with the TEC < 10-7 K-1. As a result, we can easily align the off-axis optics with the visible light and the CCD camera under the room temperature environment, which significantly reduces the cost and time for development.

The first light of VINROUGE is expected in 2018. In this paper, we introduce science cases, conceptual design, and future plan of VINROUGE. See Sarugaku et al. and Kaji et al. for the detail of the Ge-immersion grating.

9908-271, Session PS4

Precision single mode fibre integral field spectroscopy with the RHEA spectrograph

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The RHEA Spectrograph is a single-mode echelle spectrograph designed to be a replicable and cost effective method of undertaking precision radial velocity measurements. Two versions of RHEA currently exist, one located at the Australian National University (ANU) in Canberra, Australia (450 – 600nm wavelength range), and another located at the Subaru Telescope in Hawaii, USA (600 – 800 nm wavelength range). Both instruments have a novel fibre feed consisting of an integral field unit injecting light into a 2 dimensional grid of single mode fibres. This 2D grid of fibres is then reformatted into a 1D array at the input of the spectrograph (consisting of the science fibres and a reference fibre capable of receiving a white-light or xenon reference source for simultaneous calibration). The use of single mode fibres frees RHEA from the issue of modal noise and significantly reduces the size of the optics used. In addition to increasing the overall light throughput of the system, the integral field unit allows for cutting edge science goals to be achieved when operating behind the 8.3 m Subaru Telescope and the SCExAO adaptive optics system. These include, but are not limited to: resolved stellar photospheres; resolved protoplanetary disk structures; resolved Mira shocks, dust and winds; and sub-arcsecond companions. We present details and results of early tests of RHEA@Subaru and progress towards the stated science goals.

9908-272, Session PS4

Investigating the stability limitations and improving the design of iodine gas-absorption cells for exoplanet radial velocimetry

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We revisit the design, construction, and performance of iodine absorption cells frequently in use for precision radial velocity monitoring targeted to detect and characterize extra-solar planets. The project aims to investigate the stability and performance limitations of the well established yet poorly studied iodine gas-absorption cells, and to improve the design and manufacturing of contemporaneous iodine calibration cells, offering a cost-effective, high-precision simultaneous wavelength reference for optical high-resolution spectrographs.

We present the scope of the project and discuss our stability measurements as well as an improved cell design. We also demonstrate the performance of protoypes already manufactured and tested.

9908-273, Session PS4

Next generation multi-order reflective spatial heterodyne spectroscopy for broadband high resolving power spectroscopy of diffused emission line sources

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Spectral observations of the intensity and distribution of UV-Visible emission/absorption features is a staple technique for the remote sensing of comets, planetary upper atmospheres and near space environments, thin satellite atmospheres, and interactions of all of these with the solar wind and high-energy radiation field. Bandpass imaging and low resolving power spectroscopic measurements are adequate for identifying basic composition, spatial structure, and total energy input of these features. However, these measurements miss the useful information available from line shapes and ratios, including velocity distributions, thermal properties, turbulence, energetic neutral/ion populations, radiative transfer effects, isotopic ratios and contributions from multiple sources. Unfortunately, gaining access to this information is complicated by the fact that the sources under study are relatively low in energy from an astrophysical perspective and are low in surface brightness and angularly extended, particularly from the close perspective of a remote probe.

The most commonly utilized approaches for high resolving power spectroscopy, such as the cross dispersed echelle spectrometer, are typically limited in their field of view (FOV) such that they undersample extended features. As a result, their étendue relies on the input aperture of a telescope. One alternative to this is to employ an interferometric technique such as a reflective spatial heterodyne spectrometer (SHS). Reflective SHS instruments are common-path Fourier Transform Spectrometers that use a diffraction grating to split incoming light into two beams that are then interfered to obtain high resolving power spectra. Their chief advantage comes from their large relative FOV compared with other instruments that allows their use at small aperture telescopes. Their chief disadvantage comes from their limited sampling bandpass (1-10 nm).

We describe here the first results from a new SHS design that employs a high order grating to simultaneously sample a very broad spectral range (300-650 nm) with a single instrumental alignment. The instrument was constructed and tested at the McMath-Pierce solar observatory where it was used to observe several extended astronomical targets. In this report we describe the instrumental design, efficiency, and optical performance of the instrument and evaluate the multi-order technique as a potential tool for remote sensing at small aperture telescopes and space based remote probes.

9908-274, Session PS4

First high-efficiency and high-resolution NIR spectroscopy with high-blazed Echelle grating: WINERED HIRES-mode w/R80,000 commissioned

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WINERED is a PI-type NIR high-resolution and high-sensitive spectrograph. It was commissioned by Laboratory of Infrared High-resolution spectroscopy (LiH) at Koyama Astronomical Observatory in Kyoto Sangyo University, Japan, and it is currently mounted on the 1.3 m Araki Telescope located in the university campus. WINERED has the "WIDE mode" that simultaneously obtains 0.90-1.35 um spectra with the spectral resolution of 30,000 and the throughput of > 50 % (including the Q.E. of the array detector). This mode has been already completed and producing fruitful scientific results for various astronomical objects, such as comets, planets, stars, and interstellar medium (see Ikeda et al. in this conference for more details). At present, we have been developing a new mode that provides much higher spectral resolution of R ~80,000 (=HIRES mode). In general, there are two choices to achieve such high spectral resolution with grating: immersion grating and high-blazed echelle grating. We selected the latter because the fabrication is easier than immersion grating due to the looser tolerances on surface irregularity, surface roughness, and groove pitch error, although the ideal maximum diffraction efficiency is often degraded compared to that of immersion grating by about 10 %. Custom high-brazed gratings were fabricated by CANON Inc., Japan. The designed groove pitch, blaze angle, and the apex angle are 90.38 um, 79.32 deg, and 88 deg, respectively. The protected Ag is adopted for the reflective coating on the grating surface and the apex angle is set to 88 deg to compensate the unavoidable degradation of diffraction efficiency for high-blazed echelle grating due to the shadow effect. A mosaic of two gratings with the 200 mm x 60 mm ruled area is set on the pupil. The total throughput of WINERED with this grating is expected to be ~40 %. The accurate alignment of two gratings is technically challenging because the alignment tolerances are extremely tight. In particular, the parallelism of 100nm is required for the monochromatic slit-images diffracted from two gratings to be focused with the positional difference of < 1/10 pixels (the roll-angle error and the pitch-angle error between grating surfaces are 1 arcsec and 0.5 arcsec, respectively). To meet with this tight requirement, we designed a special grating holder made of an extremely low CTE material such as low expansion ceramic with an ultra-precise alignment mechanism. Since the high-blazed echelle gratings are used in the quasi-Littrow condition with the gamma angle of 6 deg, the monochromatic slit image is considerably tilted on the detector, which may result in degraded spectral resolution due to pixelization effect in the diagonal direction of the pixel. We investigate the influence and appropriate reduction methods for keeping the spectral resolution determined by optics. In this paper, we present the designed and optical performances of this HIRES mode, the reduction procedure of images obtained by this mode, and preliminary astronomical results by engineering observations.

9908-275, Session PS4

The precision radial velocity error budget for the Gemini High-resolution Optical SpecTrograph (GHOST)

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The Gemini High-resolution Optical SpecTrograph (GHOST) is a fiber fed spectrograph primarily designed for high efficiency and broad wavelength coverage (363-1000nm), with an anticipated commissioning early in 2018. The primary scientific goal of the Precision Radial Velocity (PRV) mode will be follow-up of relatively faint (R>12) transiting exoplanet targets, especially from the TESS mission. The high predicted efficiency

of GHOST will mean that it is competitive with other southern PRV instruments, especially for faint, cool stars. In the PRV mode, the 1.2 arcsec diameter stellar image will be split 19 ways, combined in a single slit with a simultaneous Th/Xe reference source, dispersed at a resolving power of ~80,000 and imaged onto two detectors. The spectrograph will be thermally stabilised in the Gemini pier laboratory, and modal noise will be ameliorated through the use of a fiber agitator. Unlike other precision high resolution spectrographs, GHOST will not be pressure controlled (although pressure will be monitored precisely), and there will be no double scrambler or shaped (e.g. octagonal) fibers. Instead, GHOST will have to rely on simultaneous imaging of the slit and simultaneous Th/Xe fiber in two filters to correct for variable fiber illumination and focal-ratio degradation. This configuration presents unique challenges in estimating a PRV error budget. We will describe all terms in this error budget, which in the most optimistic (goal) error budget are dominated by slit profile measurement errors and time-variable spectrograph aberrations. We will verify the error budget terms with simplified end-to-end simulations which include terms such as seeing variations, micro-optic fabrication uncertainties, variable focal-ratio degradation and atmospheric pressure changes. We will show that the spectrograph requirement of 10m/s PRV uncertainty is justified, and that the goal of 1m/s is plausibly within reach.

9908-276, Session PS4

Integration, alignment, and verification of the ESPRESSO front-end

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ESPRESSO, Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations, will be installed soon on ESO's VLT. The Front End modular subsystems collect the light from the CoudÃ©e Trains of all the four Telescope Units (UT), provide field and pupil stabilization via piezoelectric tip tilt driven by a reimaging system, and inject the beam into the Spectrograph fibre. The Front End will also inject the calibration light coming from the calibration unit. A toggling system is provided to switch between the different observation modes, using single or multiple UTs.

The presence of different modes shared between the four Front End Units drove the design of the system and the alignment workflow. The strategy followed to define the convergence point and the optical paths linking the Coudé trains to the six fibres are described. Once defined the reference system, all the mechanical and optomechanical components are aligned. The different procedures and methods used to align the ground plates, the main structure, the mode selector, the fibres and the Front End Units will be presented.

Finally, we evaluate the performances of the system in terms of image quality both on the Fiber Link focal plane and on TCCD used for pupil and field stabilisation, and in terms of encircled energy in the observed point spread function (PSF, fitted by a two-dimensional gaussian profile), which is directly linked with the efficiency of the light collection at the fibre plane.

9908-277, Session PS4

Integration and alignment through mechanical measurements: the example of the ESPRESSO front-end units

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Traditional techniques usually relies on optical feedback to align optical elements over all the degrees of freedom needed. This strongly iterative process imply the use of bulky and/or flexible adjustable mountings.

Another solution under study consists in the characterization of every optomechanical elements and the integration of the parts without any optical feedback. The characterization can be performed using different 3D Coordinate Measuring Machines like Laser Tracker, Articulated Arms and Cartesian ones) and referencing different parts like the optomechanical mounts or the optical surfaces. The alignment of the system is done adjusting the six degrees of freedom of every element with metallic shims. Those calibrated element are used to correct the interfaces position of the semi-kinematic system composed by 3 screws and 3 pins.

In this paper, the integration and alignment of the ESPRESSO Front End Units (FEUs) will be used as pathfinder to test different alignment methods and evaluate their performances. The FEUs are five identical system used to stabilize and inject the light of the four Unit Telescopes composing the VLT into a number of fibres. This lead to strong requirements in term of accuracy and repeatability of the alignment proving them as the perfect candidate for this study.

The alignment is done mounting any single unit on a fixed kinematic mount system and placing all the optomechanical elements in the correct position with an Articulated Arm Coordinate Measuring Machine and calibrated stainless steel shims, to reach the 50 micrometer positioning precision. The characterization of the mechanical mountings is performed with a Cartesian Coordinate Measuring Machine. The alignment is then verified and eventually refined by means of a Telescope Simulator, producing the image of the telescope field and pupil in the proper position of the FE. Encircled energy on the fibre plane and image quality of the guiding system will be presented and discussed as verification of the alignment quality.

9908-278, Session PS4

Developing and deploying an externally dispersed interferometer-test bed for visual-band, high-resolution spectroscopy on 2.0-m class telescopes

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The Externally-Dispersed Spectrograph (EDI) Testbed was developed and constructed at Tennessee State University in conjunction with the University of California, Berkley. EDI Technology has been shown to boost the effective resolution of spectrographs by a factor 10. Unlike previous installments of EDI technology, this instrument is optimized for use in the visible wavelengths, 480-620 nm. The system is a fiber-fed Michelson-type interferometer, whose outputs are then fed to an echelle spectrograph of R~4000. Data pipeline processing software has been developed to produce the desired data product from a properly constructed set of EDI images. It has been designed to be portable, cost-effective and robotically operated. Constructed using mostly off the shelf parts with a budget under 100,000 USD, this technology is easily attainable by institutions using 2.0-m class telescopes. As a testbed instrument, it has been designed to be flexible in order to test a range of configurations and so mature the EDI technology

itself. The flexibility of the system also allows for its use observing a large range of astronomical objects in addition to its intended purpose of detecting exoplanets by measuring the small Doppler shifts of their host stars caused by their orbits. The EDI-Testbed can also be used to produce high resolution spectroscopy using methods developed on previous EDI instruments (see Erskine et al 2015, http://spectralfringe.org/EDI/MyPubs3/TediTenx38twocol.pdf). The alignment and the delay of the interferometer arms are adjustable with computer controlled stages and optical mounts. Alignment maintenance can be accomplished remotely and automatically, a requirement for use on TSU's 2.0-m telescope at Fairborn Observatory. It is housed in a special built instrument room that is temperature controlled to less than 1 degree Celsius. This room has been built to house this and other instruments connected by fiber to TSU's 2.0-m Telescope. Spots are available for housing new fiber-fed guest instruments for interested institutions.

9908-279, Session PS4

The astro-comb on Chinese 216 Telescope

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The radial velocity method, based on the Doppler effect, plays an important role in the extrasolar planets searching. The astronomical spectrographs have been lacking calibration sources when searching for the twin earth. The astro-comb is emerging as a promising calibration source with significant performances leaping. After installing a GPS referenced 25GHz astro-comb from Menlosystem in Xinlong, China, We couple the output from the astro-comb into a mode scrambler employing polygon fiber and mechanical shaker. Then, the beam is relayed to the high resolution astronomical spectrograph of Chinese 2.16-m telescope. We will present our test run results.

9908-280, Session PS4

The Gemini High-Resolution Optical SpecTrograph (GHOST) bench spectrograph optical design

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The instrument group of the NRC Herzberg Astronomy and Astrophysics has been subcontracted by the Australian Astronomical Observatory to design and build the bench spectrograph for Gemini High-Resolution Optical SpecTrograph (GHOST) instrument. GHOST is the newest instrument being developed for the Gemini telescope and is a collaboration between the Australian Astronomical Observatory, the NRC Herzberg Astronomy and Astrophysics in Canada and the Australian National University (ANU). The instrument is a fiber feed spectrograph with R>50,000 in two-object mode and R>75,000 in single object mode. This paper outlines the optical design of the bench-mounted spectrograph and the predicted spectrograph resolution and efficiency for the spectrograph.

9908-281, Session PS4

Fiber link design for the NASA-NSF extreme precision Doppler spectrograph concept "WISDOM"

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We describe designs for the fiber-optic coupling and light transfer system of the WISDOM (WIYN Spectrograph for DOppler Monitoring) instrument. As a next-generation Precision Radial Velocity (PRV) spectometer, WISDOM incorporates lessons learned from HARPS about thermal, pressure, and gravity control, but also takes new measures to stabilize the spectrograph illumination, a subject that has been overlooked until recently. While fiber optic links provide more even illumination than a conventional slit, careful engineering of the interface is required to realize their full potential. Conventional round fiber core geometries have been used successfully in conjunction with optical double scramblers, but such systems still retain a memory of the input illumination that is visible in systems seeking sub-m/s PRV precision. Non-circular fibers, along with advanced optical scramblers, and careful optimization of the spectrograph optical system itself are therefore necessary to study Earth-sized planets. For WISDOM, we have developed such a state-of-the-art fiber link concept. Its design is driven primarily by PRV requirements, but it also manages to preserve high overall throughput.

Light from the telescope is coupled into a set of six, 32 micron diameter octagonal core fibers, as high resolution is achieved via pupil slicing. The low-OH, step index, fused silica, FBPI-type fibers are custom designed for their numerical aperture that matches the convergence of the feeding beam and thus minimizes focal ratio degradation at the output. Given the demanding environment at the telescope the fiber end tips are mounted in a custom fused silica holder, providing a perfect thermal match. We used a novel process, chemically assisted photo etching, to manufacture this glass fiber.

A single ball-lens scrambler is inserted into the 25m long fibers. Employing an anti-reflection (AR) coated, high index, cubic-zirconia ball lens the alignment of the scrambler components are straightforward, as the fiber end tips (also AR coated) by design touch the ball lens and thus eliminate spacing tolerances. A clever and simple opto-mechanical design and assembly process assures micron-level self-alignment, yielding a ~87% throughput and a scrambling gain of >20,000.

To mitigate modal noise the individual fibers then subsequently combined into a pair of rectangular fibers, providing a much larger modal area thanks to the 34x106 micron diameter. To minimize slit height, and thus better utilize detector area, the octagonal cores are brought very close together in this transition. The two outer fibers are side polished at one side, into a D-shaped cladding, while the central fiber has a dual side polish. These tapered, side-flattening operations are executed with precise alignment to the octagonal core. Thus the cores of the 3 fibers are brought together and aligned within few microns of each other before spliced into the rectangular fiber.

Overall throughput kept high and FRD at bay by careful management of fiber mounting, vacuum feed-through, application of efficient AR coatings, and implementation of thermal breaks that allow for independent expansion of the fibers and the protective tubing.

9908-282, Session PS4

Optical design for NEID, a proposed spectrometer for NASA's WIYN extreme precision Doppler spectrometer

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We have developed an optical design for a high resolution spectrograph in response to NASA's call for an extreme precision Doppler spectrometer (EPDS) for the WIYN telescope. Our instrument covers a wavelength range of 380 to 930nm on a single detector, with a resolution more than 100,000. To deliver the most stable spectrum, we avoid the use of an image slicer, in favour of a large ~190mm diameter beam footprint on a 1x2 mosaic R4 Echelle grating. The optical design is based on a classic white pupil layout, with a single parabolic mirror, used as main as well as transfer collimator. Cross-dispersion is delivered by a single large PBM2Y glass prism. The refractive camera is comprised of only four rotationally symmetric lenses of i-Line glass, yet delivers very high image quality over the full spectral bandpass. We present the optical design of the main spectrograph bench and discuss the design trade-offs and expected performance that enable simultaneous science, sky, and calibration fibers to be recorded on the large format CCD.

9908-283, Session PS4

Scrambling gain of non-circular core fibers being tested for use in the Stable High Resolution Echelle for Keck (SHREK) instrument

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The SHREK collaboration has been testing octagonal fibers for a new high resolution Doppler shift spectrometer. The fibers serve a number of purposes: transporting light from the telescope focus to the temperature controlled spectrometer in the basement, and scrambling the light so that guiding errors do not cause spectral line distortions or shifts. We present tests of focal ratio degradation, near and far-field fiber output patterns, and efficiencies for non-circular core fibers coupled to double scramblers and agitators.

9908-284, Session PS4

ESPRESSO AIT: a critical step toward the science

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ESPRESSO, the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations of the ESO - Very Large Telescope site, is now in its integration phase.

The assembly, integration and verification phase of ESPRESSO, due to its distributed nature and different geographical locations of the consortium partners, is quite challenging.

This paper will describe the AIT strategies of the subsystems into the complete Espresso. The activities performed and their results will be described here focusing the attention onto the experience gained and the lessons learned in the last project's phases. Preliminary performances are also presented.

9908-285, Session PS4

The HARPS-North@TNG polarimeter

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A new spectro-polarimetric unit for the High Accuracy Radial velocity Planet Searcher of North emisphere (HARPS-N) of the Telescopio Nazionale Galileo has been installed.

Electro-opto-mechanical solutions adopted to link the dual-beam spectro-polarimeter located at a Nasmyth focus to the fiber-fed spectrograph and, at the same time, able to guarantee a correct orientation of optical axes in the celestial equatorial system are described. First results of science verification are reported.

9908-286, Session PS4

First results from the MINERVA precision RV spectrograph

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The MINiature Exoplanet Radial Velocity Array (MINERVA) is a dedicated

observatory for exoplanet detection that consists of four robotic 0.7-meter telescopes located at Whipple Observatory on Mt Hopkins, Arizona. We have been doing robotic photometry, primarily of transits and microlensing, since December 2014. At the end of December 2015, we installed a purpose-built, environmentally-stabilized, high-precision iodine cell spectrometer built by Callaghan Innovations that is fiber fed simultaneously from all four telescopes to conduct a survey for small planets around the brightest RV-quiet GKM stars. The four smaller telescopes have the same collecting area as a 1.4 meter telescope at a fifth of the cost and allow greater understanding of guiding and telescope induced systematic errors. We will discuss the first results from the commissioning effort since the installation. MINERVA is a collaboration among Harvard University, Penn State University, University of Montana, and University of New South Wales.

9908-387, Session PS4

First light of a laser frequency comb at SALT

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The High Resolution Spectrograph (HRS) on the Southern African Large Telescope (SALT) is a dual beam, fiber-fed echelle spectrograph providing high resolution capabilities to the SALT observing community. Its High Stability mode has a resolution of 65000, and its standard calibration sources are a ThAr lamp and an Iodine cell. The ThAr lamp's emission lines cover two thirds of HRS' red channel wavelength range, but with sparse and severely uneven spectral line spacing. The line intensity also ranges from only a few counts above the background noise to close to saturation. The Iodine Cell provides narrower wavelength coverage: from 500 to 620 nm (roughly a third of the red channel range), but with improved line spacing and greater homogeneity in line intensity.

Here we report on a Laser Frequency Comb (LFC) which provides complete coverage of the red channel, with comb lines uniformly separated in frequency space, with good intensity homogeneity and offering unprecedented line occurrence (20 000 lines vs 400 ThAr lamp lines). The LFC is powered by a Nd:YVO4 laser centred at 1064 nm, which is frequency doubled to 532 nm. A mode-locked Ti:Sapphire laser oscillator, pumped by the Nd:YVO4 laser, generates sub-30 femtosecond laser pulses at a 1 GHz repetition rate and centred at 800 nm. The near-infrared pulses are then spectrally broadened into a super-continuum in the 2.7 micron core of a 50 cm long Photonic Crystal Fibre, yielding wavelength coverage from 550 to beyond 1000 nm. A Fabry-Pérot cavity then filters the laser modes such that the individual lines are 15 GHz apart, corresponding to ~10 pixels between successive comb lines on the HRS's red detector. A narrow linewidth diode laser is stabilised to an atomic transition in a Rb gas cell (at a wavelength of 780.24nm) and co-coupled into the spectrograph with the frequency comb to provide an absolute fiducial point for wavelength calibration.

The output beam of the frequency comb is fed into a 10 m transport fibre and directed into the HRS. This optical injection setup makes provision for effortlessly alternating between calibration sources: the ThAr lamp, the frequency comb, or both at the same time. The first on-sky observations were made 5 days after arrival at the telescope. Results obtained during a week of operation include refinement of the wavelength calibration established using only the ThAr lamp, and a revised determination of the High-Stability mode's resolution: 67000 rather than 65000. Expected results include: full calibration of the ThAr spectrum due to the possibility of obtaining frames that afford simultaneous detection of lines from the ThAr arc lamp and the LFC, improved understanding of the HRS stability and resultant radial velocity precision, and (from an engineering point of view) practical operational requirements for a LFC on a large telescope.

9908-49, Session 11

Galactic archeology with the high-efficiency and resolution multi-element spectrograph, HERMES at the AAT *(Invited Paper)*

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The High Efficiency and Resolution Multi Element Spectrograph, HERMES is a facility-class optical spectrograph for the AAT. It is designed primarily for Galactic Archeology, the first major attempt to create a detailed understanding of galaxy formation and evolution by studying the history of our own galaxy, the Milky Way. The goal of the Galactic Archeology with Hermes (GALAH) survey is to reconstruct the mass assembly history of the Milky Way, through a detailed spatially tagged abundance study of one million stars. The spectrograph is based at the Anglo Australian Telescope (AAT) and is fed by the existing 2dF robotic fiber positioning system. The spectrograph uses VPH-gratings to achieve a spectral resolving power of 28,000 in standard mode and also provides a high-resolution mode ranging between 40,000 to 50,000 using a slit mask. The GALAH survey requires a SNR greater than 100 for a star brightness of V=14. The total spectral coverage of the four channels is about 100nm between 370 and 1000nm for up to 392 simultaneous targets within the 2-degree field of view. Hermes was commissioned in late 2013, with the GALAH Pilot starting in parallel with the commissioning, The GALAH survey started in early 2014 is currently about 25% complete. We present a description of the motivating science; an overview the instrument; and a status report on GALAH Survey.

9908-50, Session 11

DESI: design considerations for a massive redshift survey

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The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14000 sq deg will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs.

DESI will measure redshifts for 35 million galaxies and 2.5 million quasars over a survey footprint of 14,000 square degrees. The focal plane is required to cover 8 square degrees in each exposure in order to map the full survey footprint.

5000 fiber positioners are required for multiplexing a sufficient number of targets in each DESI exposure. Each of 10 spectrographs split the light into 3 cameras to retain high throughput over a wavelength range spanning 360 nm to 980 nm. The blue wavelengths are designed to provide mapping of the Lyman-alpha forest at redshifts at z>2, and the red wavelengths are designed to obtain galaxy redshift to z=1.6. A resolving power of 2000 in the blue extracts most of the information from the Lyman-alpha forest. A resolving power of 5000 in the red is required to measure emission lines from galaxies between the much brighter terrestrial sky lines. This broad wavelength coverage is also required for high redshift success rates with minimal contamination of the maps with incorrect redshifts. The wide field of view, 5000-fiber multiplexing, high throughput, and an instrument reconfiguration time of one minute will allow the key project to complete in 5 years.

DESI will provide an order of magnitude improvement over previous redshift surveys in both the number of galaxies and the volume of space that is probed. This will significantly advance our understanding of the expansion history of the Universe and the effects of Dark Energy.

9908-51, Session 11

Design of the DESI focal plane system

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The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14000 sq deg will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs. We describe here the Focal Plane System, which contains the 5000 robotic fiber positioners, 6 guide cameras, 4 wavefront cameras, 120 fiducial point sources, and a metrology camera, mounted at the primary mirror, which surveys the precise positions of these items for every observation. The system has 365,135 moving parts, and 778,709 parts total. The density of the instrument is such that 99.96% of these parts are contained within an envelope volume of only 0.4 m?. We explain here the overall architecture, the functions and interfaces of each of the subcomponents, and integration and operation of the system. The instrument will be constructed in 2017, and commissioned in 2018.

9908-52, Session 11

Hector: a massive new IFU instrument for the Anglo-Australian Telescope

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Hector will be the new massively-multiplexed integral field instrument for the Anglo-Australian Observatory in Australia and the next main dark-time instrument for the observatory. Based on the success of the SAMI instrument, which is undertaking a large 3400-galaxy survey, the IFU imaging fibre bundle (hexabundle) technology under-pinning SAMI is being improved to a new innovative design. The distribution of hexabundle angular sizes is matched to the galaxy survey properties in order to image 90% of galaxies out to 2 effective radii. 50-100 of these IFU imaging bundles will be positioned by `Starbug' robots across a new 3-degree field top end to be purpose-built for the AAT. Many thousand fibres will then be fed into new replicable spectrographs.

Fundamentally new science will be achieved compared to existing instruments due to Hector's wider field of view (3 degrees), high positioning efficiency using starbugs, higher spectroscopic resolution (R=3000-5500 from 3727-7761 Angstroms, with a possible redder extension later) and large IFUs (up to 30" diameter with 61-217 fibre cores).

Hector will decipher the diversity of galaxies through understanding their individuality.

A 100,000 galaxy IFU survey will decrypt how the accretion and merger history and large-scale environment made every galaxy different in its morphology and star formation history.

The high resolution, particularly in the blue, will make Hector the only instrument to be able to measure higher-order kinematics for galaxies down to much lower velocity dispersion than in current large IFU galaxy surveys, opening up a wealth of new nearby galaxy science.

The science requirements are complete and both the spectrograph design and the 3 degree field top end optical and mechanical design have reached concept design review stage. The adaptation of single-fibre starbugs to now hold a larger fibre bundle is also underway. Hector is targeted for completion in ~2020.

9908-53, Session 11

Final design and progress of WEAVE: the next generation wide-field spectroscopy facility for the William Herschel Telescope

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We present the Final Design of the WEAVE next-generation spectroscopy facility for the William Herschel Telescope (WHT), together with a status update on the details of manufacturing, integration and the overall project schedule now that all the major fabrication contracts are in place. We also present a summary of the current planning behind the 5-year initial phase of survey operations. WEAVE will provide optical ground-based follow up of ground-based (LOFAR) and space-based (Gaia) surveys. WEAVE is a multi-object and multi-IFU facility utilizing a new 2-degree prime focus field of view at the WHT, with a buffered pick-and-place positioner system hosting 1000 multi-object (MOS) fibres, 20 integral field units, or a single large IFU for each observation. The fibres are fed to a single (dual-beam) spectrograph, with total of 16k spectral pixels, located within the WHT GHRIL enclosure on the telescope Nasmyth platform, supporting observations at R~5000 over the full 370-1000nm wavelength range in a single exposure, or a high resolution mode with limited coverage in each arm at R~20000. The project is now in the manufacturing and integration phase with first light expected for the end of 2017.

9908-54, Session 12

VIRUS: first deployment of the massively replicated fiber integral field spectrograph for the upgraded Hobby-Eberly Telescope

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The Visible Integral-field Replicable Unit Spectrograph (VIRUS) consists of 156 identical spectrographs (arrayed as 78 pairs) fed by 35,000 fibers, each 1.5 arcsec diameter, at the focus of the upgraded 10 m Hobby-Eberly Telescope (HET). VIRUS has a fixed bandpass of 350-550 nm and resolving power R~700. VIRUS is the first example of industrial-scale replication applied to optical astronomy and is capable of surveying large areas of sky, spectrally. The VIRUS concept offers significant savings of engineering effort, cost, and schedule when compared to traditional instruments.

The main motivator for VIRUS is to map the evolution of dark energy for the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX), using 0.8M Lyman-alpha emitting galaxies as tracers. The VIRUS array is undergoing staged deployment during 2016. It will provide a powerful new facility instrument for the HET, well suited to the survey niche of the telescope, and will open up large spectroscopic surveys of the emission line universe for the first time. We will review the production, lessons learned in reaching volume production, characterization and first deployment of this massive instrument.

9908-55, Session 12

VIRUS early installation and commissioning

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VIRUS is a massively replicated spectrograph built for HETDEX, the Hobby Eberly Telescope Dark Energy Experiment. It consists of 156 channels within 78 units fed by 34944 fibers over the 22 arcminute field of the upgraded HET. VIRUS covers a relatively narrow bandpass (350-550nm) at low resolution (R~700) to target the emission of Lyman-alpha emitters (LAEs) for HETDEX. VIRUS is a first demonstration of industrial style large scale assembly line replication in optical astronomy.

Installation and testing of VIRUS units began in November of 2015. This winter we celebrated the first on sky instrument activity of the upgraded HET, using a VIRUS unit and LRS2-R (the upgraded facility Low Resolution Spectrograph for the HET). Here we describe progress in VIRUS installation and commissioning through June 2016. We walk through achievements of each installation batch, including integration and testing of the VIRUS enclosures via long-term vacuum and temperature performance. We include early sky data obtained to characterize spectrograph performance and on sky performance of the newly upgraded HET. As part of the instrumentation for first science light at the HET, the IFU fed spectrographs were used to test a full range of telescope system functionality including the field calibration unit (FCU). We also use placement of strategic IFUs to map the new HET field to the fiber placement, and demonstrate actuation of the dithering mechanism key to HETDEX observations.

9908-56, Session 12

EMIR at the GTC: results on the commissioning at the telescope

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We report the results on the EMIR performances after the commissioning period of the instrument at the GTC. EMIR is one of the first common user instruments for the GTC, the 10 meter telescope operating at the Roque de los Muchachos Observatory (La Palma, Canary Islands, Spain). EMIR is being built by a Consortium of Spanish and French institutes led by the Instituto de Astrofi?sica de Canarias (IAC). EMIR is primarily designed to be operated as a MOS in the K band, but offers a wide range of observing modes, including imaging and spectroscopy, both long slit and multiobject, in the wavelength range 0.9 to 2.5 ?m. The development and fabrication of EMIR is funded by GRANTECAN and the Plan Nacional de Astronomi?a y Astrofi?sica (National Plan for Astronomy and Astrophysics, Spain).

After an extensive and intensive period of system verification at the IAC, EMIR is shipped to the GTC for its integration at the Nasmyth platform. Once in the observatory, many tests are being conducted to ensure the functionality of EMIR at the telescope, in particular that of the ECS (EMIR Control System) which has to be fully embedded into the GCS (GTC Control System) so as to become an integral part of it. During the commissioning, the main capabilities of EMIR and its combined operation with the GTC are tested and the ECS are modified to its final form. This contribution reports on the details of the EMIR operation at the GTC obtained so far.

9908-57, Session 12

MEGARA, the new intermediate-resolution optical IFU and MOS for GTC: getting ready for the telescope

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MEGARA is the new optical spectrograph for the 10.4m GTC telescope that will soon offer to the community Integral-Field Unit (IFU) and Multi-Object Spectroscopy (MOS) capabilities within the entire optical window (360nm-970nm) with resolutions ranging from R=6000 to R=20000. MEGARA will be installed at GTC before the end of 2016.

The MEGARA IFU (also called the Large Compact Bundle) fully covers an area of 12.5 x 11.3 arcsec^2 with hexagonal spaxels of 0.62" arcsec in diameter while the MOS is composed by a total of 92 robotic positioners (with each positioner equipped with a 7-spaxel mini-IFU) that move independently within overlapping patrol areas that all together cover an area of 3.5 x 3.5 arcmin^2, i.e. the flat and non-vignetted Field-of-View of the GTC Folded-Cass focus. The light is conducted by means of optical fibers to the MEGARA spectrograph that is kept static on the Nasmyth platform of GTC. Thanks to the use of high-efficiency optical fibers, state-

of-the-art VPH gratings and detector and to the large(st) collecting area of GTC, MEGARA will be unique for carrying out chemo-dynamical studies of very faint targets, both point-like and extended. The instrument is now in AIV phase at the LICA laboratory of the Universidad Complutense de Madrid and it will be shipped to GTC this upcoming November.

MEGARA is being developed by a Consortium of institutions led by the Universidad Complutense de Madrid (UCM) but also includes the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE, Mexico), the Instituto de Astrofísica de Andalucía (IAA-CSIC, Spain) and the Universidad Politécnica de Madrid (UPM, Spain). The instrument is financed by GRANTECAN S.A. (the public company in charge of the operation of GTC) and by the Consortium institutions.

In this talk I will present the main characteristics of the instrument and provide details on the status and results of the AIV phase, both at subsystem and already at system level. Laboratory acceptance is scheduled for September 2016.

9908-58, Session 12

MIRADAS for the Gran Telescopio Canarias: overview

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MIRADAS (Mid-resolution InfRAreD Astronomical Spectrograph) is the facility near-infrared multi-object echelle spectrograph for the Gran Telescopio Canarias (GTC) 10.4-meter telescope. MIRADAS operates at spectral resolution R=20,000 over the 1-2.5μm bandpass), and provides multiplexing (up to N=12 targets) and spectro-polarimetry. The MIRADAS consortium includes the University of Florida, Universidad de Barcelona, Universidad Complutense de Madrid, Instituto de Astrofísica de Canarias, Institut d'Estudis Espacials de Catalunya and Universidad Nacional Autonoma de Mexico, as well as partners at A-V-S (Spain), New England Optical Systems (USA), and IUCAA (India). MIRADAS completed its Final Design Review in 2015, and in this paper, we review the current status and overall system design for the instrument, with scheduled delivery in 2018. We particularly emphasize key developments in cryogenic robotic probe arms for multiplexing, a macro-slicer mini-IFU, an advanced cryogenic spectrograph optical system, and a SIDECAR-based array control system for the 1x2 HAWAII-2RG detector mosaic.

9908-59, Session 13

Prime Focus Spectrograph (PFS) for Subaru Telescope: overview, recent progresses, and future perspectives

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PFS (Prime Focus Spectrograph), a next generation facility instrumentis on the 8.2m Subaru Telescope, is a very wide-field, massively multiplexed, and optical & near-infrared (NIR) spectrograph.

Exploiting the Subaru prime focus, 2400 reconfigurable fibers will be distributed in the 1.3 deg field of view. The spectrograph has been designed to cover a wide range of wavelengths simultaneously from 380nm to 1260nm at one exposure.

On the Subaru Telescope, Hyper Suprime-Cam (HSC), a very wide-field imager on the prime focus, has already been in science operation and a 5-years survey program in the framework of Subaru Strategic Program (SSP) is on-going. PFS and HSC are in fact the instrumentation projects under the Subaru Measurement of Images and Redshifts (SuMIRe) project to conduct deep and wide sky surveys exploiting the unique capability of the Subaru Telescope. PFS is therefore expected to start in a timely manner subsequently after the HSC SSP survey. It should be emphasized that HSC and PFS enable deep imaging and spectroscopic surveys of the same patches of sky using the same 8.2m telescope, allowing one to have good understandings of various systematics that should be considered for physical interpretations of the data.

The PFS instrument consists of a few subsystems. The Prime Focus Instrument (PFI) will be installed in the same Prime Focus housing unit "POpt2" with the Wide Field Corrector (WFC) lens system mechanically integrated (i.e. WFC will be used for PFS as well as HSC). PFI accommodates the fiber posioner system which populates 2394 science fibers on the focal plane with the "Cobra" actuators. In the process of configuring fibers to science targets on sky, all the science fibers and fiducial fibers will be backlit and then the fiber tips will be imaged all at one exposure from the Cassegrain port by the Metrology Camera System

(MCS), which enables quick fiber configuration. The Spectrograph System (SpS) will receive the light tranmitted in the fiber system from the prime focus and deliver their spectral images on the detectors. SpS has four identical modules each of which will accept 600 fibers. Using the two dichroic mirrors, the beam from the pseudo fiber slit will be split into the blue, red, and NIR cameras. The fiber system is devided into three sections via the two sets of fiber connectors both are of contact type. While the middle section will permanently stay on the telescope, either side is a part of PFI or SpS.

The development of this instrument has been undertaken by the international collaboration at the initiative of Kavli IPMU. The project is now going into construction, integration and test aiming at starting system integration in 2017, engineering operations in 2018, and science operation from 2019. In parallel, detailed modeling of the instrument and output spectral images activities of instrument and data modeling are on-going in order to are on-going in order to characterize the instrument on-sky capabilities and accordingly mature the SSP survey design. In this contribution, an overview of the instrument, current project status and future perspectives will be presented.

9908-60, Session 13

MOONS: towards the VLT's next generation of multi-object spectrograph

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When MOONS arrives at the VLT in a few years time it will provide the European community with a revolutionary new tool to tackle a wide range of Galactic, extragalactic and cosmological questions. This remarkable instrument will simultaneously deliver ~1000 optical and near infrared spectra from across the full 500 square arcmin field of view of the VLT. In its low resolution mode (R>4000) MOONS will provide almost complete spectral coverage from 0.65 - 1.8?m, while a high resolution mode will allow detailed abundance analysis of the CaT (R~9000) and in the H-band at R~18,000. The objects are coupled to the spectrograph through optical fibres, deployed with a host of individual small robotic positioners that will provide both excellent field coverage and very fast configuration times. This paper will provide an update on the instrument's current design, with all of its evolutions, challenges and successes.

9908-61, Session 13

4MOST: the 4-metre Multi-Object Spectroscopic Telescope project at preliminary design review

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We present an overview and status update of the 4MOST project as presented at the Preliminary Design Review. 4MOST is a major new wide-field, high-multiplex spectroscopic survey facility under development for the VISTA telescope at the Paranal Observatory of ESO. Starting in 2021, 4MOST will deploy 2436 optical fibres in a 4.1 square degree field-of-view using a fibre positioner based on the tilting spine principle. The fibres will feed one high-resolution (R~20,000) and two medium-resolution (R~5000) spectrographs that all have fixed configuration, 3-channel designs with identical 6k x 6k CCD detectors.

The 4MOST science goals are mostly driven by a number of large area, space-based observatories of prime European interest: Gaia and PLATO (Galactic Archeology and Stellar Physics), eROSITA (High-Energy Sky), and Euclid (Cosmology and Galaxy Evolution). These main science cases drive the nine Consortium Surveys covering a large fraction of the Southern sky, with bright time mostly devoted to the Milky Way disk and bulge areas and the Magellanic Clouds, and the dark/gray time essentially devoted to extra-galactic targets. In addition there will be a significant fraction of the fibre-hours devoted to ESO Community Surveys, making 4MOST a true general-purpose survey facility, capable of delivering spectra of samples of objects that are spread over a large fraction of the sky.

The 4MOST Facility Simulator was created to show the feasibility of the innovative operations scheme of 4MOST with all surveys operating in parallel. The simulator uses the mock catalogues created by the science teams, simulates the spectral throughput and detection of the objects, assigns the fibres at each telescope pointing, creates pointing distributions across the sky and simulates a 5-year survey (including overhead, calibration and weather losses), and finally does data quality analyses and computes the science Figure-of-Merits to assess the quality of science produced. The simulations prove the full feasibility of running different surveys in parallel.

9908-64, Session 13

Mauna Kea Spectrographic Explorer (MSE): conceptual design of multi-object high resolution spectrograph

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The Maunakea Spectroscopic Explorer (MSE) project will transform the CFHT 3.6m optical telescope into a 10m class dedicated multi-object spectroscopic facility, with an ability to simultaneously measure thousands of objects with a spectral resolution range spanning 2,000 to 40,000. MSE will develop two spectrographic facilities to meet the science requirements. These are, respectively, the Low/Medium Resolution spectrographs (LMRS) and High Resolution spectrographs (HRS). Multi-object high resolution spectrographs with total of 1156 fibers is big challenge, one that has never been attempted for a 10m class telescope. To date, most of spectral survey facilities over the world work in single order low/medium resolution mode, and only a few Wide Field Spectrographs (WFS) provide a cross-dispersion high resolution mode with a limited number of orders. Nanjing Institute of Astronomical Optics and Technology proposes a conceptual design with the use of novel image slicer arrays and single order immersed VPH grating for MSE HR Multi-Object Spectrographs (MOS). The conceptual scheme contains three identical fiber-link spectrographs, each of which simultaneously covers two restricted (about 20nm) bands in the optical regime, with a spectral resolution of 38000 – 42000. The details of the design will be given in this paper.

9908-65, Session 13

ULTIMATE: a deployable multiple integral field unit for Subaru

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ULTIMATE is an instrument concept under development for the Subaru Telescope, which will have the unique combination of ground layer adaptive optics feeding multiple deployable integral field units. This will give ULTIMATE a unique parameter space, in terms of number of IFUs and spatial resolution, enabling science cases such as the evolution of galaxies at z~0.5 to 1.5, and the dark matter content of the inner part of our Galaxy.

ULTIMATE will use Starbugs to position between 7 and 13 IFUs over a 14 x 8 arcmin field-of-view, provided by a new wide-field corrector. Each IFU will consist of a fore-optics feeding a 61 element hexagonally packed microlens array, providing a pupil image onto a fibre array. These components will be housed in a Starbug positioner, a semi autonomous robotic positioner, that moves over a field plate at the f/12 Cassegrain focus. All Starbugs can be positioned simultaneously, to an accuracy of better than 5 milli-arcsec within the typical slew-time of the telescope, allowing for very efficient re-configuration between observations. Each microlens will subtend 0.15 arcsec on the sky.

The IFUs will feed either the nuMOIRCS or the PFS spectrographs, or both. The fibres will form a pseudo-slit inside the spectrograph dewar, via a vacuum feed-through, to minimise thermal emission. The image from each fibre will be relayed onto the spectrograph slit proper. For the

NIR nuMOIRCS spectrograph we are investigating the possibility of using ZBLAN fibres to provide spectroscopy over the full J,H and K bands. In particular, ZrF4 fibres are now available which have better than 90% transmission over the full J, H and K bands for a 30m length, and 98% transmission at 2.5 microns, and FRD properties commensurable with silica fibres. The handling of such fibres, and end-face treatment, remain issues to be further investigated. Future possible upgrades include the possibilty of OH suppression using fibre Bragg gratings.

9908-184, Session 13

Feasibility study of GMOX: a next-generation instrument for Gemini

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We present the feasibility study of GMOX, the Gemini Multi-Object eXtra-wide-band spectrograph, funded to help Gemini craft the requirements for the next facility instrument (Gen~4#3). We envision GMOX as a spectrograph covering the entire optical/near-IR wavelength range accessible from the ground (from 3500 A in the U-band up to 2.4 micron in the K-band) with nominal resolving power R~5,000, adequate to mitigate the effect of telluric airglow lines. Using existing Digital Micromirror Device (DMD) technology, GMOX can simultaneously acquire hundreds of spectra of faint sources in crowded fields with unparalleled spatial resolution. GMOX optimally adapts to both seeing-limited and diffraction-limited conditions provided by ALTAIR and GeMS at Gemini North and South, respectively. On a large fraction of nights, these systems deliver nearly diffraction-limited imaging in the near-IR (lambda/D=50 mas at 2micron) and exquisite, seeing-limited images across the visible. Fed by GeMS (f/33), GMOX can synthesize slits as small as 40mas (corresponding to a single HST/WFC3 CCD pixel) over its entire 85.2x45.2 arcsec field of view, reaching the ultimate sensitivity to point sources while resolving structures smaller than 300 pc across the observable Universe. Both the slit and field size double at the native f/16 focal ratio of Gemini. Leveraging on studies to bring DMD technology to fruition for future space missions, GMOX can deliver unique science and superior performance at a lower cost than any competing IFU or multi-slit spectrograph.

9908-62, Session PS5

Optical design of MEMS-based infrared multi-object spectrograph concept for the Gemini South Telescope

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We discuss the optical design of an infrared multi-object spectrograph concept that is designed to take advantage of the multi-conjugate adaptive optics (MCAO) corrected field at the Gemini South telescope. This design employs a unique, cryogenic MEMS-based focal plane mask, a Micro-Shutter Array (MSA) that has been developed for the Near Infrared Spectrometer of the James Webb Space Telescope, to select target objects for spectroscopy. Our optical design is based on all spherical refractive optics, which serves both imaging and spectral modes across the wavelength range of 0.9-2.5 μm. The optical system consists of a reimaging system, the MSA, a collimator, volume phase holographic (VPH) grisms, and spectrograph camera optics. The VPH grisms, which are VPH gratings sandwiched between two prisms, provide high dispersing efficiencies, while a set of four different VPH grisms provide the broad spectral coverage at high throughputs. The imaging mode is implemented by removing the MSA and the dispersing unit out of the beam. We optimize both the spectrographic and imaging modes simultaneously, while paying special attention to the performance of the pupil imaging at the cold stop. Our current design provides a 1' ? 1' and a 0.5' ? 1' field of views for imaging and spectral modes, respectively, on a 2048 ? 2048 pixel HAWAII-2RG detector array. Its slit width and spectral resolving power are 0.18" and 3,000, respectively, and spectra of up to 100 objects can be obtained simultaneously. We present the results of simulated performance of this spectrograph's optical design.

9908-287, Session PS5

Performance characteristics of a suite of volume phase holographic gratings produced for the Subaru prime focus spectrograph

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The Subaru Prime Focus Spectrograph requires a suite of volume phase holographic (VPH) gratings that parse the observational spectrum into three sub-spectral regions. In addition, the red region has second, a higher resolution design. This paper describes the specifications of the four grating types, gives the expected theoretical performances of diffraction efficiency for the production designs and presents the actual measured performances on the production gratings.

The three spectral regions cover the overall range from 380 nm (blue) into the near infrared at 1260 nm. Four gratings each of four different grating designs were manufactured for the Subaru PFS for a total of sixteen gratings. The lowest grating deigns operate from 380 to 650 nm, the next from 630 to 970 nm and the highest from 940 to 1260 nm. This paper shows the RCWA theoretical predictions for each of the designs and presents the test data for each of the gratings built.

9908-288, Session PS5

The Dark Energy Spectroscopic Instrument (DESI) instrument mechanism control systems

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The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14,000 sq deg will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5,000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs. We will describe the design details of the spectrograph mechanism control system. Each spectrograph has a stand-alone mechanism control system that operates the unit's four remotely-operated mechanisms (two shutters and two Hartmann doors), including an inflatable shutter seal and fiber illumination system, and provides a suite of temperature and humidity sensors. Each control system is highly modular, and is operated by a dedicated on-board Linux computer to provide all of the control and monitoring functions. We describe our solution for integrating a number of network-connected devices within each unit spectrograph, and describe the basic software architecture.

9908-289, Session PS5

Fusion splicing: a novel approach to fiber connections for the Dark Energy Spectroscopic Instrument

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The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14000 sq deg will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5000 fiber optic positioners. The fibers will run 40 meters from the focal plane to the coude ? room where they feed ten broad-band spectrographs. The focal plane assembly will be integrated independently of the spectrograph slits and long fiber cables in order to ease integration flow, and the two subsystems will be connected before final integration on the telescope. In order to retain maximum throughput and minimize the focal ratio degradation (FRD) when connecting the fiber system, we are employing fusion splicing as opposed to mechanical connectorization. For the best splice performance, the optical fibers are stripped of their polyimide coating, precision cleaved, and then fused with a heating filament. We report results from the splicing process, measuring a collimated FRD increase of less than 0.5 degrees for a f/3.9 input beam compared to >1 degree increase for mechanical connectors. We also show that the near field performance is not degraded after splicing. These results represent the first of their kind for a fiber-fed astronomical instrument.

9908-290, Session PS5

The MOONS-VLT Spectrometer: toward the final design

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MOONS, the Multi-Object Optical and Near-infrared Spectrograph for the VLT, is entering into the final design phase.

This paper presents and discusses the latest proposed version of the optical design of the cryogenic spectrograph. The main developements and modifications were aimed at minimizing the overall size and mass of the cryogenic spectrometer. The most remarkable new feature is the design of an extremely fast (F/0.95), light and compact (40 kg in less than 80 dm^3) camera with superbe image quality (80% encircled energy within <20 microns) over a very large field of view (9 degrees on a collimated beam of 265 mm). The camera consists of only 3 optical elements: 2 lenses and 1 mirror. All elements are made of fused-silica. The optical performances are independent on the temperature, i.e. the camera can be fully characterized at room temperatures.

9908-291, Session PS5

Slit tests for FOCCoS, PFS, Subaru

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The Fiber Optical Cable and Connector System, "FOCCoS", subsystem of the Prime Focus Spectrograph, "PFS", for Subaru telescope, is responsible to feed four spectrographs with a set of optical fibers cables. The light injection for each spectrograph is assured by a convex curved slit with a linear array of 616 optical fibers. In this paper we show tests made with a different design of a slit that ensures the right direction of the fibers by using masks of micro holes. This kind of mask is made by a technique called electroforming, which is able to produce a nickel plate with holes in a linear sequence. The precision error is around 1-?m in the diameter and 1-?m in the positions of the holes. This nickel plate may be produced with a thickness between 50 and 200 microns, so it may be very flexible. This flexibility allows the mask to be bent into the shape necessary for a curved slit. The concept requires two masks, which we call Front Mask, and Rear Mask, separated by a gap that defines the thickness of the slit. The pitch and the diameter of the holes define the linear geometry of the slit; the curvature of each mask defines the angular geometry of the slit. Tests with the prototype include FRD analysis, Absolut Transmission of the fibers, and aiming fibers error, in room temperature and low temperature.

9908-292, Session PS5

The DESI shutter with integrated fiber illumination system

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The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14000 sq deg will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs. We will describe the unique shutter design that incorporates a fiber illumination system into its closed blade position. When activated, the fiber illumination system directs intense 430-480nm wavelength light at the instrument's fiber slit in order to back-illuminate the telescope's focal plane and verify the location of the robotic fiber optic positioners. The back-illumination is typically active during science exposure read-outs and therefore requires the shutter to attenuate light by a factor of at least 10^9. This paper describes how we have integrated the fiber illumination system into the shutter blade, as well as incorporated an inflatable seal around the shutter aperture to achieve the light attenuation requirement. We also present lab results that characterize the fiber illumination and shutter attenuation. Finally, we discuss the control scheme that distinguishes between exposure and fiber illumination modes, and meets the shutter timing requirements.

9908-293, Session PS5

Developments in fiber positioning technology for the WEAVE instrument at the William Herschel Telescope

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As the WEAVE project for the William Herschel Telescope completes the final design review phase the fibre positioner sub-system has completed is rapidly entering its procurement and manufacturing phase. Wee present an update of the final design decisions and report on the technological prototyping that has taken place. This includes fast, accurate centre finding algorithms for fibre images, improved pick and place sequencing and flexure compensation.

9908-294, Session PS5

4MOST low-resolution spectrograph: design and performances

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4MOST, the 4m Multi Object Spectroscopic Telescope, is an upcoming optical, fiber-fed, MOS facility for the VISTA telescope at ESO's Paranal Observatory in Chile. Its main science drivers are in the fields of galactic archeology, high-energy physics, galaxy evolution and cosmology. The preliminary design of 4MOST features 2436 fibers split into low-resolution (1624 fibers, 370-950 nm, R > 4000) and high-resolution spectrographs (812 fibers, three arms, ~44-69 nm coverage each, R > 18000) with a fiber positioner and covering an hexagonal field of view of ~4.1 deg?. The 4MOST consortium consists of several institutes in Europe and Australia under leadership of the Leibniz-Institut für Astrophysik, Potsdam (AIP). 4MOST is currently in its Preliminary Design Phase with an expected start of science operations in 2021.

The 1600 fibres go to two Low Resolution Spectrographs with three channels per spectrograph. Each low resolution spectrograph is composed of 812 scientific fibers using 85µm core fibers at f/3, a 200mm beam for an off-axis collimator associated to its Schmidt corrector, 3 arms with f/1.73 cameras and standard 6k x 6k 15µm pixel detectors. CRAL has the responsibility of the Low Resolution Spectrographs.

In this paper, the optical design and performances of 4MOST Low Resolution Spectrograph will be presented. Special emphasis will be put on the Low Resolution Spectrograph system budget and performance analysis.

9908-295, Session PS5

Integration and testing of DESI multi-object spectrograph

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The DESI project (Dark Energy Spectroscopic Instrument), under LBNL leadership, is one of the main programs of observational cosmology, which aims at understanding the nature of the "dark energy" responsible for the acceleration of the expansion of the Universe. DESI will survey more than 20 millions of objects in the sky thanks to its multi-object spectrograph fed by 5,000 robotically controlled fiber-positioners covering 360 nm to 980 nm. The DESI spectrograph, actually consisting of 10 units with 3 arms each, will be installed on the 4-m Mayall telescope at Kitt Peak in 2018.

An Aix-Marseille University consortium, bringing together three CNRS laboratories from Marseille, France, namely LAM, OHP and CPPM, has committed to deliver a fully validated spectrograph prototype, the first of a series of 10 units, with a view to validating the integration of all its constituents and the instrumental performances before building the other nine spectrographs. This validation will take place at Winlight, who is in charge of the production of the optical spectrograph near Marseille, a close combination, which is certainly an advantageous approach in terms of risk reduction. In the integration phase, all integration procedures and interfaces between constituents will be validated. During the scientific qualification phase, many performance tests will be conducted, including focus adjustment procedure and verification, image quality, spectral resolution, spectra position and size, fiber separation, thermal performance of the whole system, cross-talk between the 3 arms and between adjacent spectra, straylight, second order contamination. Additional tests will also be possible to help scientists prepare the pipeline with the evaluation of the PSF and the throughput of the spectrograph. The experience gained from the first spectrograph will allow us to optimize the "integration and qualification" process for the other nine spectrographs.

For these purposes, a dedicated test equipment taking into account both the integration and qualification phases has been defined with a view to fulfill the compliance matrix and verify the design requirements. It has lead to the development of a multi-purpose and flexible test bench, which allows to feed the fiber test slit so as to perform all the required tests. It simulates the fiber inputs incoming from the telescope, offers continuum and line sources, and it allows to adjust the flux level and to choose to illuminate one or several fibers. It is fully automated and interfaced with the global ICS system. Dedicated analysis tools have also been developed, both initial monitoring to validate the quality of the data and more specific tools according to the DESI configuration. All these developments will be described in details and first results will be presented.

9908-296, Session PS5

ProtoDESI: risk reduction experiment for the Dark Energy Spectroscopic Instrument

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The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14000 sq deg will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs. We describe the ProtoDESI experiment, planned for installation and commissioning at the Mayall telescope in the fall of 2016, which will test the fiber positioning system for DESI. The ProtoDESI focal plate, consisting of 8 fiber positioners, illuminated fiducials, and a guide, focus and alignment (GFA) sensor module, will be installed behind the prime focus corrector. A Fiber View Camera (FVC) will be mounted to the lower surface of the primary mirror cell and a subset of the Instrument Control System (ICS) will control the ProtoDESI subsystems, communicate with the Telescope Control System (TCS), and collect instrument monitoring data. Short optical fibers from the positioners will be routed to the back of the focal plane where they will be imaged by the Fiber Photometry Camera (FPC) or back-illuminated by a LED system. Target objects will be identified relative to guide stars, and using the GFA in a control loop with the ICS/TCS system, the guide stars will remain stable on pre-identified GFA pixels. The fiber positioners will then be commanded to the target locations and placed on the targets iteratively, using the FVC to centroid on back-illuminated fibers and fiducials to make corrective delta motions. When the positioners are aligned with the targets on-sky, the FPC will measure the intensities from the positioners' fibers and can then be dithered to look for intensity changes indicating how well the fibers were initially positioned on target centers. The final goal is to operate ProtoDESI on the Mayall telescope for a 6-hour period during one night, successfully placing targets on > 75% of the intended fibers.

9908-297, Session PS5

Integration and characterization of the cryogenic system of MEGARA

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MEGARA (Multi-Espectrógrafo en GTC de Alta Resolución para Astronomía) is an optical Integral-Field Unit and Multi-Object Spectrograph designed for the GTC (Gran Telescopio de Canarias) 10.4 m telescope in La Palma, it is expected that the spectrograph will be delivered to GTC towards the end of 2016. The LN2 open-cycle cryostat of the instrument has been designed by the "Astronomical Instrumentation Lab for Millimeter Wavelengths" at the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE) in Mexico. According to the design, the MEGARA cryostat should have a hold time of 40 hours or more to keep operating the scientific CCD at 150 K. The cryostat has finished its fabrication and now it is on AIV phases. In this paper we summarize the cryostat integration method, the adjustment procedure of the kinematic CCD support, the tests related with its general operation at cryogenic temperatures and the thermal link behavior from the LN2 tank to the CCD mounting, as well as pressure characterization performance.

9908-298, Session PS5

Towards the cryogenic sliding mechanism for MOONS-ESO

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The Multi-Object Optical and Near-Infrared Spectrograph (MOONS) shall be installed at one of the Very Large Telescopes (VLT) at the European Southern Observatory (ESO) in Paranal Chile. The instrument is being designed and built by an international consortium on behalf of ESO. The design is based on a three arms configuration, RI, YJ and H band, where RI and H have two possible resolutions. To achieve this goal it will be necessary to implement a sliding mechanism changing the dispersers, the filters and the cross dispersion prisms. This article describes the cryogenic exchanger mechanism that is under realization and the preliminary mechanical and optical tests that we have done at the cryogenic facility of Arcetri observatory of Florence. Parts of these test are based on interferometric measurements of the optics to study the behaviour of the mechanical supporting structure, and part are based on the cryogenic sliding system that will be used to move approximately 200 Kg of mass for 350 mm of travel range. The cryogenic sliding system, rails, screws, motors, is based on commercial components as the position measurement device that is based on commercial potentiometers. The results of the tests and performances at cryogenic temperature are reported in this paper.

9908-299, Session PS5

VIRUS characterization development and results from first batches of delivered units

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The Visible Integral Field Replicable Unit Spectrograph (VIRUS), the instrument for the Hobby Eberly Telescope Dark Energy Experiment (HETDEX), consists of 78 replicable units, each with two integral field spectrographs. Each spectrograph has its own 2kx2k CCD detector with 15 micron pixels. Following alignment, the final stage prior to deployment of each unit is characterization of the 156 spectrograph channels and their CCDs. We describe the laboratory calibration system and scripting that automates this process. Both fiber and continuous (non-spatially modulated) input slits are utilized. Photon transfer curves are made to measure the gain and read noise of each CCD. Pixel flats are also made to correct for pixel-to-pixel QE variations. Throughput measurements of each unit are made using the same lab fiber bundle for consistency, and fiber profiles are characterized for later use by the Cure data reduction package. Replicable unit instruments provide a cost effective solution for scaling up instruments for large and extremely large class telescopes. Because VIRUS is the first massively replicated instrument, we have the opportunity to examine the end result of variations in the manufacturing processes that go into production. This paper presents the characterization setup for VIRUS units and compares the performance and variability of processed units with specifications for HETDEX.

9908-300, Session PS5

The current status for metroloogy camera system of Subaru prime focus spectrograph

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The Prime Focus Spectrograph (PFS) is a new optical/near-infrared multi-fiber spectrograph designed for the prime focus of the 8.2m Subaru telescope. PFS will cover 1.3 degree diameter field with 2394 fibers to complement the imaging capability of Hyper SuprimeCam. To retain high throughput of PFS, the final positioning accuracy between the fibers and observing targets of PFS is required to be less than 10 microns. The metrology camera system (MCS) serves as the optical encoder of the fiber motors for the configuring of fibers. MCS provides the fiber positions within 3 microns error over the 45 cm focal plane. The information from MCS will be fed into the fiber positioner control system for the close loop control.

MCS locates at the Cassegrain focus of Subaru telescope to cover the whole focal plan with one 50M pixel Canon CMOS camera. It is a 380mm Schmidt type telescope which generats uniform spot size around 10 microns FWHM across the field for reasonable sampling of the point spreading function. Carbon fiber tubes are used to provide stable structure over the operation conditions without focus adjustments. The CMOS sensor can be read in 0.8s to reduce the overhead for the fiber configuration. The positions of all fibers can be obtained within 0.5s after the readout of the frame. This enables the overall fiber configuration to be less than 2 minutes. MCS will be installed inside a standard Subaru Cassgrain Box. All components generate heat are located inside a glycol cooled cabinet to reduce the possible image motion due to the heat. The optics and camera for MCS have been delivered and tested. The mechanical parts and support structure are ready in spring 2016. The integration of MCS will start in the summer of 2016.

In this report, the performance of MCS component, the alignment and testing procedure as well as the status of the PFS MCS will be presented.

9908-301, Session PS5

The current status of prime focus instrument of Subaru prime focus spectrograph

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The Prime Focus Spectrograph (PFS) is a new optical/near-infrared multi-fiber spectrograph designed for the prime focus of the 8.2m Subaru telescope. PFS will cover 1.3 degree diameter field with 2394 fibers to complement the imaging capability of Hyper SuprimeCam (HSC). The prime focus unit of PFS called Prime Focus Instrument (PFI) provides the interface with the top structure of Subaru telescope and also accommodates the optical bench in which Cobra fiber positioners locate. In addition, acquisition and guiding cameras (AG cameras), center viewing camera, cable wrapper, field element, fiducial fiber illuminators and telemetry system are located inside the PFI. The flat fielding and spectrum calibration lamps are positioned on the top of PFI.

Being at the prime focus environment of Subaru telescope, tight space, weight and heat dissipation constraints are applied to PFI. Furthermore, the structure stiffness of PFI is also limited to avoid any possible damage of the fragile ceramic lens barrel of the wide field corrector. A combination of different materials at different locations in height is used in PFI to provide a stable focal plane position over the operation temperature range (5 to -5 degree C) of PFS. A glycol based cooling system removes the heat generated from the electronics of various components of PFI to avoid the possible seeing degradation. To share the same wide field corrector with HSC, a flat glass called field element is added in front of the fibers for compensating the optical path difference.

Six FLI ML4720 cameras are installed at the periphery of the effective field for field acquisition and guiding. With 1s exposures, each AG camera can provide at least 2 guide stars at any pointing of the sky. A 0.9mm BK7 glass is installed inside each camera to cover half of the CCD sensor to accelerate the focus sequence. Together with the tiny 0.7 mm center viewing camera, AG cameras provide essential information for the pointing and distortion map of the focal plane. The relative distance between the AG camera sensors to the reference fiducial fibers is calibrated and kept

stable within 5 microns with different operation conditions to meet the alignment requirement of the fibers. A high brightness red LED with a light diffusor is used as the light source to illuminate 20mm diameter area of 96 fiducial fibers. The integration and verification of PFI starts in early 2016. The integration and testing of the Cobra positioner modules will take about 13 months. The position and the angle of each fiber will be measured to the precision of 10 microns in x, y, z directions and 0.17 degrees in tilt at the operation temperature range and with different elevation angles. Such information will provide important calibration data for the fiber configuration during the operation.

In this report, the latest status of PFI development will be given including the performance of PFI components, the setup and performance of the integration and testing equipment, and the progress of PFI integration work.

9908-302, Session PS5

Developing multi-fibers connectors device for FOCCoS-PFS-Subaru

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The Fiber Optical Cable and Connector System (FOCCoS), provides optical connection between 2400 positioners and a set of spectrographs through optical fibers cables as part of PFS instrument for Subaru telescope. The optical fiber cable will be segmented in 3 parts along the route, cable A, cable B and cable C, connected by a set of multi-fiber connectors. The company USCONEC produces the multi-fiber connector under study. The USCONEC 32F model can connect 32 optical fibers in a 4 x 8 matrix arrangement. The ferrules are made of a durable composite, Polyphenylene Sulfide (PPS) based thermoplastic. The connections are held in place by a push-on/pull-off latch, and the connector can also be distinguished by a pair of metal guide pins that protrude from the front of the connector. Two fibers per connector will be used for monitoring the connection procedure. It was found to be easy to polish and it is small enough to be mounted in groups.

Highly multiplexed instruments like PFS require a fiber connector system that can deliver excellent optical performance and reliability. PFS requires two different types of structures to organize the connectors. The Tower Connector system, with 80 multi-fiber connectors, will be a group of connectors for connecting cable B (Telescope Structure) with cable C (Positioners Plate). The Gang Connector system is a group of 8 gang connectors, each one with 12 multi-fibers connectors, for connecting cable B (Telescope Structure) with cable A (Spectrograph). The bench tests with these connector systems and the chosen fibers should measure the throughput of light and the stability after many connections and disconnections. In this paper we describe possible tests and procedures to evaluate the throughput and FRD increment. The lifetime of the ferrules is also in evaluation.

9908-303, Session PS5

iSHELL: a 1-5 micron R=70,000 immersion grating spectrograph for IRTF

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iSHELL is a 1-5 micron cross-dispersed echelle spectrograph being built for the 3-m NASA Infrared Telescope Facility (IRTF) on Maunakea, Hawaii. The instrument is currently undergoing all-up testing and is scheduled for first light in 2016. It is a white pupil spectrograph that produces measured resolving powers of up to R=75,000 matched to a 0.375" slit. In order to keep iSHELL small enough to be mounted at the Cassegrain focus of the telescope, dispersion is accomplished with a silicon immersion grating, fabricated at the University of Texas, Austin. The blaze angle is 71.6 degrees (R3) with an entrance aperture of 30 mm x 35 mm to accommodate a collimated beam diameter of 22 mm diameter. Except for gaps in the deep telluric features centered at 2.6 and 4.4 microns the entire 1.15-5.3 micron wavelength range is covered in 17 settings with seven first-order tilt-able cross-dispersing gratings, in combination with a slit wheel and dekker mechanism. Slit widths of 0.375", 0.75", 1.5" and 4.0", and slit lengths of 5", 15" and 25", are available. One Teledyne 2048x2048 Hawaii 2RG array is used in the spectrograph, and one Raytheon 512x512 Aladdin 2 array is used in a slit viewer for object acquisition and guiding.

The cryostat contains three major optical assemblies: the foreoptics, the slit viewer and the spectrograph. A warm calibration system consisting of calibration lamps, integrating sphere and illumination optics is mounted on top of the cryostat vacuum jacket. The foreoptics and slit viewer are mounted on one side of a cold optical bench and the spectrograph to the opposite side. Liquid nitrogen cools the optics and optical bench to 75K to keep the instrument background below the detector dark current of 0.1 e/s. The first stage of a closed-cycle cooler cools a radiation shield surrounding the optical bench enclosure while the second stage cools the spectrograph and slit viewing detectors to 37K and 30K respectively. Eight mechanisms run by cold motors are mounted on the optical bench. The size of the vacuum jacket is 1.3 m x 0.6 m x 0.7 m and the instrument weighs about 600 kg (not including ancillary electronics).

Astronomical Research Camera (ARC) Generation 3 controllers are used to run both arrays. The H2RG spectrograph array is wired for 32 channels and the smaller InSb slit-viewer array is wired for 8 channels. Each of the array controllers is controlled with a dedicated PC. Observers interface with iSHELL via GUIs that run on the spectrograph and slit-viewer PCs.

iSHELL is designed to do a variety of science across 1-5 micron including planetary atmospheres, comets, exoplanets, protostellar objects and stars. It is optimized for observations at 3-4 microns. This paper discusses the design, and performance and characterization of iSHELL in the lab.

9908-304, Session PS5

Performance of MEGARA spectrograph optical elements

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MEGARA is the new IFU and multi-object spectrograph for GTC. The spectograph will offer spectral resolution R=6,000-20,000 thanks to a spectrograph design based in the used of volume phase holographic gratings in combination with prisms to keep fixed the collimator and camera angle. Except for the optical fibers and micro lenses, the complete MEGARA optical system has been manufactured in Mexico, shared between the workshops of INAOE and CIO. This includes a field lens, a 5-lenses collimator, a 7-lenses camera, four of them of CaF2. It also includes a complete set of volume phase holographic gratings with 36 flat windows and 24 prisms. All these elements are very large and complex, with very efficient anti reflection coatings. The optomechanics of the collimator and camera was also manufactured in Mexico. The optical performance of MEGARA spectrograph elements and of the collimator and camera as subsystems will be described

9908-305, Session PS5

Design and testing of AR coatings for MEGARA optics

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Antireflection (AR) coatings are fundamental in the design of astronomical instruments. The purpose of such coatings is to reduce reflection and to increase the transmission properties of the optical surfaces to improve optical efficiency in a specific spectral band. In this work we present the AR coating design procedure for the optical elements of MEGARA, the integral field and multi-object spectrograph for the Gran Telescopio de Canarias (GTC). In this instrument, the AR coatings are particularly challenging, due to the fact that the main optics require a wide spectral band coverage at very low reflectivity.

The methodology for optimizing the solutions at particular angles of incidence and the testing of the final deposited coatings is presented. The main optics of the spectrograph require broadband coatings in the wavelength range from 370 to 980 nm for materials ranging from Nd=1.43 to Nd=1.83 with an average reflection less or equal to 1.3% at distinct angles of incidence (AOI) in each surface, this was achieved by design of eight layer AR coatings. The pupil elements of the instrument consist of prisms and windows for which four layer AR coatings were designed and produced aiming for an average reflection as low as 0.3% in distinct spectral bands, defined by the different spectral configurations: six for low resolution (LR), ten for medium resolution (MR) and two for high resolution (HR).

Regarding main optic elements, for each substrate, AR coatings consisting in a specific arrangement of thicknesses of eight layers of different materials were produced and tested in witness samples prior to the final evaporation. For the pupil elements, the LR windows are already evaporated with their final coatings, for the MR and HR prisms the designs are ready and are currently being tested towards final evaporation.

For the testing of the coatings a spectrophotometer was used to determine the total transmission of each element, then a method for the subtraction of the Fresnel losses is implemented, finally the total surface reflectance is reported. The measurements are obtained at AOI=0 and then extrapolated to the desired AOI, depending on each element.

We provide the results of the testing of the AR coatings of the main optics and the LR windows. The designs have been effectively tested using a method of analysis to implement the subtraction of the Fresnel effects. In most of the spectral band the AR coatings exceed the performance requirements and the average reflectance is equal or less than 1.3% for. The main optics elements are undergoing final coatings, and the pupil element coatings for MR and HR are currently under testing. A further analysis will be made with the final depositions to estimate the total average transmittance of the optics system.

9908-306, Session PS5

The Australian ESO positioner (AESOP) for 4MOST facility on the Vista Telescope

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We present the Australian ESO Positioner (AESOP) for 4MOST facility on the Vista telescope. AAO is part of the multi-national 4Most consortium whose goal is to outfit the Vista telescope with a massively multiplexed wide-field spectroscopic capability to solve a wide range of scientific problems, including cosmology, galaxy evolution, high-energy and galactic science. For 4Most, AESOP will position 2400 fibers over a hexagonal field-of-view of 4 square degrees (2.5 degree diameter) feeding two sets of spectrographs at R=5000 and R=20,000. AESOP is based on the patented Echidna 'tilting spine' fiber positioner technology that has been in operation since 2007 on the SUBARU telescope in the FMOS system. An update to the AESOP project, which is in Critical Design Phase will be presented along with throughput comparisons to other positioner types, where we find that losses due to tilt are generally outweighed by the increased allocation yield, greater patrol area and reduced fiber stress FRD of the Echidna design.

9908-307, Session PS5

Optical design for the TAIPAN and HECTOR transmissive spectrographs

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TAIPAN is a multi-fibre project for the UK-Schmidt telescope and Hector is a multi-IFU project for the Anglo-Australian Telescope (AAT) using fibres. Many different transparent designs were studied covering a large parameter space. An important trade-off study was for the use of microlenses on the slit or not. Microlenses have disadvantages but permit considerable simplification of the collimator by making the beam very slow. The disadvantages are more important with the UK-Schmidt due to the faster beam from the telescope. With microlenses, the collimator is a unique spherical plano-convex lens significantly smaller than the mirror that would be needed in a reflective design. For Hector, 24 different camera designs where done to cover the parameter space for 2k x 2k, 2k x 4k, or 4k x 4k detectors, and for 50, 75 or 100 micron fibre cores, with or without microlenses, with a triplet in the camera or a doublet plus singlet, and with a maximum wavelength of 1 or 1.05 microns. Not all combinations were designed but for each parameter there are at least two representative cameras with all other parameters identical. This permits, in principle, the identification of the minimal cost design. Also, a theoretical study was done of the PSF obtained with highly packed microlenses at the slit with no space between them and imaging to 2 pixels per microlenses. This maximizes the number of fibres per spectrograph, and thus the total field of view of all IFUs together, but it comes with some disadvantages.

9908-308, Session PS5

Wide-field corrector for 4MOST: design details and MAIV processes

Nicolas Azais, Gregory A. Smith, Samuel C. Barden, Leibniz-Institut für Astrophysik Potsdam (Germany); Bernard-Alexis Delabre, European Southern Observatory (Germany); Damien J. Jones, Prime Optics (Australia); Sylvain Egron, Aix-Marseille Univ. (France) and ONERA (France) and Space Telescope Science Institute (United States)

4MOST is a wide-field, high-multiplex spectroscopic survey facility under development for the VISTA telescope of the European Southern Observatory (ESO). Its main science drivers are in the fields of galactic archeology, high-energy physics, galaxy evolution and cosmology. In particular, 4MOST will provide the spectroscopic complements to the large area surveys coming from space missions like Gaia, eROSITA, Euclid, and PLATO and from ground-based facilities like VISTA, VST, DES, LSST and SKA. The 4MOST baseline concept features a 2.5 degree diameter field-of-view with ~2400 fibres in the focal surface, configured by a tilting spine fibre positioner.

The primary and secondary mirrors (M1&M2) together with the Wide Field Corrector (WFC) system provide a pupil-centric and aberration corrected focal surface. The WFC incorporates an atmospheric dispersion corrector utilizing two wedge lenses moving independently in rotation around the optical axis. The WFC is also an integral part of the metrology system, which permits determination of fiber positions in the focal plane.

At the focal plane, two wave front sensing (WFS) systems obtain aberration data used to maintain accurate figure on M1. At commissioning, a deployable camera will move along the focal surface to provide high order wavefront information verifying the performance of the WFC. A permanently mounted pair of low order wavefront sensor cameras provides information for M2 positioning. An acquisition and guiding (A&G) unit provides images for science field acquisition, for auto guiding and for monitoring plate scale changes and distortions (e.g. from atmospheric dispersion). Secondary guiding is provided using guide fibres interspersed within the science field.

This paper provides an overview of design details and Manufacture, Assembly, Integration and Verification (MAIV) processes for the 4MOST WFC system.

9908-309, Session PS5

DESI-GFA test bench for the CCDs characterization

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The DESI instrument (Dark Energy Spectroscopic Instrument) will be devoted to measure the effect of the dark energy on the expansion of the universe and it will be installed on the Mayall 4-meter telescope at Kitt Peak National Observatory starting in 2018.

One of the key parts of this instrument is the subsystem named DESI-GFA (Guiding, Focusing and Alignment) which is composed of ten small cameras distributed along the DESI focal plane and using one e2v CCD230-42 type each one, which is back-illuminated and 2k by 2k pixels and readout with a custom readout electronics developed from scratch at IFAE up to the readout speed of 750 KHz. The image area of this CCD has four separately sections which allow to readout the CCD in full frame and frame transfer modes by the four output amplifiers located at the top and bottom edges of the CCD. For guiding issues, it is foreseen to readout the CCD with several regions of interest (ROI) by split frame transfer mode through four amplifiers.

In order to perform the acceptance tests and then characterize the CCDs for our purposes while debugging clocks and bias signals, there was build a small cryostat with capacity to allocate one CCD at a time and able to be readout with a standard MONSOON/panVIEW solution.

Despite that the CCDs for the DESI-GFA are expected to be use at room temperature, there is necessary to perform the acceptance tests at -25 ºC, on that way, the CCD located at the cryostat focal plane will be cooled down by means a couple of Peltier elements which heat is dissipated using a cold water closed cycle system. The final element to control and stabilize the temperature is a Lakeshore controller using a 50W heater and a silicone diode temperature sensor both located just behind the CCD.

On the focal plane, the CCD will be illuminated with a flat field tool and the characterization will include some standard tests as the Photon Transfer Curve (PTC), Charge Transfer Efficiency (CTE), Dark Current tests covering a wide range of temperatures (from -25 ºC up to 30 ºC), Conversion Factor (Gain) calculated by means of a Fe-55 radioactive source and a short Quantum Efficiency test with just few wavelength points using colored light emitting diodes (led) already included in the flat field tool.

Once developed the custom readout electronics, it would be attached to the cryostat and connected to the CCD by means a DSUB50 pins hermetic connector, which will allow us to re-characterize a tested CCD with our system and compare results.

This paper will present the full setup layout, its description and the CCD characterization main results.

9908-310, Session PS5

4MOST preliminary instrument design

Steffen Frey, Olga Bellido-Tirado, Samuel C. Barden, Joar G. Brynnel, Dionne M. Haynes, Roger Haynes, Andreas Kelz, Allar Saviauk, Olivier Schnurr, Jakob C. Walcher, Gregory A. Smith, Roland Winkler, Roelof S. de Jong, Leibniz-Institut für Astrophysik Potsdam (Germany)

The systems engineering team of the "4-meter Multi-Object Spectroscopic Telescope" (4MOST) presents the preliminary design of the instrument in development. Systems engineering is part of the 4MOST project office at the Leibniz-Institut für Astrophysik Potsdam (AIP). We intend to pass the preliminary design review in 2016.

4MOST will be manufactured, assembled and verified, starting in 2017 with the purchase of long lead items for the subsystems, and finishing with the initial system verification at AIP in 2020. The instrument will then be transported to and installed, commissioned and verified at the "Visible and Infrared Survey Telescope for Astronomy" (VISTA), part of ESO's Paranal Observatory in Chile, in 2021.

The 4MOST instrument will provide more than 2400 separately movable fiber apertures located in an optically and atmospheric dispersion corrected wide field at the Cassegrain focus of VISTA. One high resolution spectrograph with a spectral resolving power R > 18000 and two low resolution spectrographs with R ~ 5000 will each image more than 800 spectra. The spectrographs are three camera arm designs. Each of the two low resolution spectrographs will cover a spectral range from 400 to 885 nm each, without gaps. The high resolution spectrograph has 3 separated wavelength ranges covering 392.8 to 435.5 nm in the blue, 516 to 573 nm in the green and a 69 nm wide band in the red.

The installation and interface of 4MOST to VISTA is challenging because the telescope was originally optimized optimized for the VIRCAM infrared wide field camera system. Active Optics and guiding sensors have to be rebuilt and accommodated within 4MOST, because they are currently part of VIRCAM. A secondary guiding system will be added to ensure the accurate positioning of the fiber apertures on the targets during the

exposure times of about 20 minutes, that are much longer than the current VISTA observations.

This paper is focused on the system design and performance drivers of the 4MOST instrument in preliminary design. We present crucial system budgets, simulation results and trade-offs which are incorporated in the presented design. We o present key parameters such as: the anticipated optical throughput, pointing accuracy, homogeneity of aperture transmission, homogeneity of spectral response, wavelength calibration, overhead at night time, availability and reliability of 4MOST.

We acknowledge and explicitly appreciate the contributions from all parties of the 4MOST consortium to the system and subsystem design of the 4MOST instrument. The design is based on the work of many excellent minds, not all of whom are authors of this paper.

9908-311, Session PS5

The alignment and assembly of the DESI prime focus corrector

David Brooks, Univ. College London (United Kingdom); Robert W. Besuner, Lawrence Berkeley National Lab. (United States); Peter Doel, Univ. College London (United Kingdom); Brenna L. Flaugher, Giuseppe Gallo, Gaston Gutierrez, Stephen Kent, Fermi National Accelerator Lab. (United States); Michael Lampton, Michael E. Levi, Lawrence Berkeley National Lab. (United States); Ming Liang, National Optical Astronomy Observatory (United States); Timothy N. Miller, Lawrence Berkeley National Lab. (United States); David Sprayberry, National Optical Astronomy Observatory (United States); Andrew Stefanik, Fermi National Accelerator Lab. (United States)

The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14000 sq deg will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs.

The prime focus corrector consists of six lenses that range in diameter from 0.80 – 1.14 meters and from 83 – 237 kg in weight. The alignment of the lenses of the optical corrector poses a significant challenge as in order to meet the fiber throughput goals they have to be positioned to a tolerance of 75 micrometers. This paper details the design for lens cells and the alignment and assembly procedure for the mounting of the lenses into the cells and into to the complete barrel assembly. This is based on the experience obtained from the alignment of the DECam instrument which was successfully assembled and aligned by the same team and we include in the paper the lessons learnt and design modifications that will be implemented on the DESI system

9908-312, Session PS5

The prime focus corrector for dark energy spectroscopic instrument

Peter Doel, David Brooks, Univ. College London (United Kingdom); Robert W. Besuner, Lawrence Berkeley National Lab. (United States); Brenna L. Flaugher, Giuseppe Gallo, Gaston Gutierrez, Stephen Kent, Fermi National Accelerator Lab. (United States); Michael Lampton, Lawrence Berkeley National Lab. (United States); Ming Liang, National Optical Astronomy Observatory (United States); Michael E. Levi, Timothy N. Miller, Lawrence Berkeley National Lab. (United States); David Sprayberry, National Optical Astronomy Observatory (United States); Andrew Stefanik, Fermi National Accelerator Lab. (United States)

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This paper describes the overall design and construction status of the prime focus corrector. The size and complexity of the system poses significant design and production challenges and the solutions adopted to these are presented. The optics of the corrector consists of six lenses, ranging from 0.8 - 1.14m in diameter, two of which can be rotated to act as an atmospheric dispersion corrector. These lenses are mounted in custom cells, designed to give low thermally induced stresses, that in turn are mounted in a barrel assembly. The barrel is mounted on a hexapod system which can actively position it to a few micrometers precision. The whole assembly will be mounted at the prime focus of the Mayall 3.8m telescope at Kitt Peak observatory and will be one of the largest lens systems ever built for an optical telescope. Construction of the corrector began in 2014 and is well advanced. The system is due to be delivered to the telescope for installation in early 2018.

9908-313, Session PS5

Implementation of the metrology system for MOONS

Holger Drass, Leonardo Vanzi, Miguel Torres-Torriti, Rolando Dünner Planella, Tzu-Chiang Shen, Francisco I. Belmar, Lousie C. Dauvin, Tomás Staig, Jonathan A. Antognini, Mauricio Flores, Yerko Luco, Pontificia Univ. Católica de Chile (Chile); Steven M. Beard, David M. Montgomery, UK Astronomy Technology Ctr. (United Kingdom); Alexandre Cabral, Mahmoud Hayati, Manuel Abreu, Univ. de Lisboa (Portugal); Philip Rees II, UK Astronomy Technology Ctr. (United Kingdom); Michele Cirasuolo, European Southern Observatory (Germany); William D. Taylor, Alasdair E. Fairley, UK Astronomy Technology Ctr. (United Kingdom)

The Multi-Object Optical and Near-infrared Spectrograph (MOONS) is a new fiber-fed spectrograph for the VLT. MOONS will exploit the full 500 square arcmin field of view offered by the Nasmyth focus of VLT and will be equipped with two dual-arm spectrographs covering the wavelength range 0.645 ?m-1.8 ?m. Each double-arm spectrograph will produce spectra for 500 targets simultaneously. To ensure the accurate positioning of the 1000 fibers over the focal plane that has 880 mm in diameter, a metrology system has been designed to provide position measurements within ~10 ?m. The paper presents the hardware and software design of the metrology system as accepted by the end of the preliminary design phase and subsequent improvements. The metrology system is based on the analysis of images taken by a circular array of 12 cameras located close to the VLT's derotator ring around the Nasmyth focus. The system includes 24 individually adjustable lamps . The fiber positions are measured through dedicated metrology targets mounted on top of the fiber positioning units (FPU) and fiducial markers connected to the FPU support plate which are imaged at the same time. A flexible pipeline based on VLT standards is used to process the images. The image processing includes target identification, filtering of stray light contamination and false positives. The resulting catalogs contain the position of the metrology targets hampered

by the distortion of the camera's CCD chip. Using information from off-line camera characterization the pipeline corrects the target positions. The final coordinates are used as input for a least square minimization algorithms to calculate the camera position making use of the known fiducial positions and then the position of the fibers on the plate. The method is validated by comparisons with an independent metrology system. The position accuracy was determined to ~5 um in the central region of the images. Including the outer regions the overall positioning accuracy is ~25 um. The MOONS metrology system is fully set up with a working prototype. The results in parts of the images are already excellent. By using upcoming hardware and improving the calibration it is expected to fullfill the accuracy requirement over the complete field of view for all metrology cameras.

9908-314, Session PS5

Impact of optical distortions on fiber positioning in the dark energy spectroscopic instrument

Stephen Kent, Fermi National Accelerator Lab. (United States); Michael Lampton, Timothy N. Miller, Space Sciences Lab. (United States); Peter Doel, David Brooks, Univ. College London (United Kingdom); Robert W. Besuner, Space Sciences Lab. (United States); Joseph H. Silber, Lawrence Berkeley National Lab. (United States); Charles Baltay, David Rabinowitz, Yale Univ. (United States); David Sprayberry, Ming Liang, National Optical Astronomy Observatory (United States)

The Dark Energy Spectroscopic Instrument (DESI), currently under construction, will measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14000 sq deg will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs.

A six-element corrector gives a useful field-of-view of 3.2 degrees diameter. A fiber view camera located near the primary mirror is used to image and measure the positions of back-illuminated fibers relative to a set of known fiducials; the absolute positioning on the sky is achieved with six guider CCDs. A major challenge is dealing with the large amount of distortion introduced by the optics (of order 10% scale change), including non-axisymmetric distortions introduced by the atmospheric dispersion compensator (ADC). This work describes all the effects that need to be tracked in mapping the focal plane to the sky, including astronomical and atmospheric effects, time-varying distortion patterns, figure and polishing errors in the corrector lenses, corrector assembly misalignments, and offsets between the fiber view camera and main camera centroids. Solutions are presented to measure or mitigate these effects.

9908-315, Session PS5

The MEGARA fiber MOS positioning tool

Jorge Iglesias-Páramo, Isaac Morales Durán, Instituto de Astrofísica de Andalucía (Spain); África Castillo Morales, Armando Gil de Paz, Univ. Complutense de Madrid (Spain); Esperanza E. Carrasco Licea, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Jesús Gallego Maestro, Univ. Complutense de Madrid (Spain); Francisco Manuel Sánchez-Moreno, Univ. Politécnica de Madrid (Spain); María Luisa García Vargas, FRACTAL S.L.N.E (Spain)

MEGARA (Multi Espectrógrafo en GTC de Alta Resolución para Astronomía) is the future optical Integral-Field Unit (IFU) and Multi-Object Spectrograph (MOS) for the 10.4-m Gran Telescopio CANARIAS (GTC).

MEGARA at the GTC will be the first instrument providing Multi Object Spectroscopy (MOS) based on robotic positioners (RPs) in a 10m-class telescope, a unique feature in terms of on-target observing time.

The MEGARA Fiber MOS Positioning Tool (FMPT) is a software suite designed to (i) confirm that the assignment of the MEGARA Robotic Positioners (RPs) for a given observing configuration issue from the Fiber MOS Assignment Tool (FMAT, also presented in this meeting) is free from dynamic collisions, and (ii) to compute the sequence of movements of the MEGARA RPs from the parking positions to the configuration defined by the FMAT, avoiding dynamic collisions between adjacent RPs. The inverse sequence of movements that will send the RPs to the parking positions is also computed. These two functionalities will be executed by the GTC staff from the FMPT Stand Alone Application, which is a command line application that makes use of the FMPT library.

In addition to this, two more functionalities have been designed for the FMPT to be performed if any of the RPs is stopped by any non expected reason: (iii) to generate a depositioning sequence that moves all the enabled RPs to security positions, and (iv) to regenerate a new positioning sequence (and the corresponding depositioning sequence) for the current observing block with all the available RPs when it is still possible. These two last functionalities will be automatically called by the MEGARA Control System in the case of necessity.

A complete description of the capabilities of the FMPT as well as the compatibility with the FMAT will be described in this talk. The performance of the FMPT will be illustrated with real time examples based on real scientific cases.

9908-316, Session PS5

The MIRADAS macro-slicer optical and opto-mechanical design

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We present the innovative macro-slicer optical and opto-mechanical designs for the MIRADAS instrument, the second-generation Mid-resolution InfraReD Astronomical Spectrograph for the 10.4m Gran Telescopio Canarias in the 1-2.5 micron bandpass. MIRADAS uses up to 12 cryogenic, fully steerable probes to select simultaneous targets in a 5 arcminute field of view. The probe arms use a collimator-camera relay to slightly speed up the native F/17 beam from the telescope to an F/14.2 beam at the macro-slicer input. The macro-slicer is a 2:1 relay which rearranges the 12 disparate inputs from the probe arms into a tightly-packed pseudo-longslit for the spectrograph module input. The spectrograph module is a cross-dispersed echelle spectrograph. The macro-slicer is effectively an advanced image slicer IFU and, like other IFUs designed and built at the University of Florida, uses a 'bolt-and-go' approach to minimize alignment challenges and maximize robustness. The 'bolt-and-go' approach developed at UF puts the onus of alignment in the opto-mechanical design/fab phase, rather than the assembly and integration phase. Because our mirrors are monolithically constructed out of aluminum blocks, we are able to add in mounting pads, tapped bolt holes, and dowel pin holes whose location precision with respect to the optical system is limited only by the machining process. The MIRADAS macro-slicer uses three sets of mirrors that work together to geometrically rearrange the very loosely packed inputs from the probe arms into a tightly packed psuedo-slit: Slicer mirrors, which live at the focal plane; pupil mirrors, which are at the pupil plane of the slicer mirrors; field mirrors, which live at the focal plane produced by

the slicer and pupil mirrors. The macro-slicer also functions to maintain the spectral resolution of MIRADAS fixed at R>20,000 with simultaneously excellent throughput in seeing conditions from 0.4-1.2 arcsec (typical at GTC in the near-infrared). We accomplish this with three slices, each 0.4 arcseconds wide, and multiplex two probes per slicer module. There are 6 slicer modules in total. Each slice has its own pupil mirror with its own tip/tilt and radius of curvature (although all radii of curvature are within 5% of the average radius). The field mirrors are unpowered, but have individual tip/tilts to correct for minor telecentric errors introduced by the IFU optics. There are 6 field mirrors per slicer (and thus 6 per set of 2 probes, 36 in total). Each field mirror is one slice of one probe. The field mirrors are also staggered slightly from one set of 6 to another. This stagger partially compensates for the tilt introduced by the geometry of the cross-dispersed echelle at the detector plane and allows us to tightly pack the spectra onto the detector.

9908-317, Session PS5

4MOST fiber feed preliminary design: prototype testing and performance

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The 4MOST instrument is a multi-object-spectrograph for the ESO-VISTA telescope. Its fibre subsystem is a central part of the facility, and is situated between the fibre positioner at the Cassegrain instrument rotator of the VISTA telescope and the spectrographs. It facilitates the transport of the light from the science targets (imaged) at the focal surface of the telescope to the slits of the 4MOST spectrographs.

The full fibre subsystem is composed of the fibre postitioner (AESOP), based on the Echidna (FMOS) tilting spine concept, and the fibre cable, which feeds two low-resolution spectrographs and one high-resolution spectrograph. The positioner holds 2436 science fibres and 12 guide spines containing 7 fibres each. They are arranged in a hexagonal pattern of which 1624 science fibres are feeding the two low-resolution spectrographs and 812 science fibres are feeding the high-resolution spectrograph. The fibre mapping scheme is complex and has been driven by the desire to have fibres for each spectrograph evenly distributed across the entire telescope field of view, as this mapping negates the risk of field loss if a spectrograph is offline for technical reasons. The focal plane (positioner) to spectrograph mapping has a significant impact on the fibre feed and dictates much of the fibre layout, modularity and routing. Fibre connectors are being used in order to facilitate 4MOST assembly, integration, maintenance as well as the VISTA primary mirror removal for re-coating.

In order to optimize the fibre feed subsystem design and provide essential information required for the spectrograph design, prototyping and testing has been undertaken. In this paper we give an overview of the current fibre feed subsystem design and present the preliminary FRD, scrambling, throughput and system performance impact depending on fibre-spine tilt, fibre connectors, de-rotator simulator and fibre cable lifetime tests.

9908-318, Session PS5

Progress on the fabrication of the DESI corrector optics

Timothy N. Miller, Lawrence Berkeley National Lab. (United States); Peter Doel, David Brooks, Univ. College London (United Kingdom); Michael J. Sholl, Lawrence Berkeley National Lab. (United States)

The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14000 sq deg will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs. We will describe the status of the DESI corrector optics, a series of 0.8 to 1.1-meter fused silica and borosilicate lenses currently being fabricated to demanding requirements. We will describe the specs for lenses that are finished or underway, including surface figure, homogeneity, and other parameters; the current schedule for lens production; verification testing; and a comparison against DESI corrector requirements.

9908-319, Session PS5

Commissioning of VIRUS integral-field units at the Hobby-Eberly Telescope

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VIRUS is the visible, integral-field replicable unit spectrograph for the Hobby-Eberly-Telescope (HET). It consists of modular spectrographs, that are being fed by 78 optical fiber-bundle IFUs, to enable the Dark Energy survey HETDEX.

In 2016, the VIRUS instrument is being deployed in modular batches at the upgraded wide-field HET. The 20 meter long fiber-bundles connect the prime focus with the spectrographs, mounted at the telescope structure. We descibe the installment and commissioning procedure of the VIRUS-IFUs. The on-sky results are compared to data from the acceptance testing in the laboratory prior shipment to evaluate the performance of the IFUs.

9908-320, Session PS5

MEGARA fiber MOS assignment tool (FMAT)

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FMAT is the tool developed by MEGARA Instrument Team to assist observers during the GTC-MEGARA proposal preparation in the MOS mode. This software allows instrument users to optimally assign targets to MEGARA fiber positioners.

FMAT starts from a list of targets with their corresponding scientific priority assigned by the user. FMAT allows to position and rotate the focal plane over the astronomical region of interest; it then allows to manually assign sources to positioners or to perform automatic assignations based

on the sources priority. Once the user is satisfied with the result of the assignment, the tool allows to produce the needed files to be sent to GTC telescope for Phase-2. The tool is also capable to assess whether a given configuration is reachable and produces and errors report. FMAT has a very intuitive GUI and an easy and flexible workflow, which allows users to iteratively assign and optimize their observations while maximizing the scientific return of the instrument.

9908-321, Session PS5

MEGARA exposure time calculator

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MEGARA (Multi-Espectrógrafo en GTC de Alta Resolución para Astronomía) is an optical Integral-Field Unit (IFU) and Multi-Object Spectrograph (MOS) designed for the GTC 10.4m telescope in La Palma. We present in this talk the capabilities of the MEGARA Exposure Time Calculation (ETC), which will provide the potential users with the necessary tool for preparing an observing program. MEGARA ETC is a web-based tool (written in Python) that computes realistic estimates of the SNRs and limiting magnitudes, for a given input source, instrumental setup, and observing conditions of the run. It also provides estimates on the required exposure times to achieve a given SNR in the continuum or in an emission line of an input source, as well as simulated spectra observed with MEGARA at a certain setup from an input library of possible astronomical objects.

The ETC has into account several instrumental effects: (i) the transmission of the telescope; (ii) the instrument transmission, accounting for that of the lenslets, the fibers, the internal optics, and the VPHs; (iii) the detector quantum efficiency as a function of wavelength; (iv) the spatial and spectral profiles in one voxel on the detector to estimate maximum and minimum SNRs.

Moreover, the tool includes the effects of the atmospheric and observing conditions of the run. In particular, they account for: (i) the atmospheric transmission as a function of the wavelength in the observatory; (ii) the effect of airmass on the light absorbed by the atmosphere in the observatory; (iii) the atmospheric extinction in the observatory; (iv) the sky emission background depending on the night of the run (if it is dark, grey, or bright); (v) the seeing of the night, considering the effect of airmass on it.

The performance of the MEGARA ETC will be illustrated with some examples based on real scientific cases.

9908-322, Session PS5

MEGARA control system

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MEGARA (Multi-Espectrógrafo en GTC de Alta Resolución para Astronomía) is an optical Integral-Field Unit (IFU) and Multi-Object Spectrograph (MOS) designed for the GTC 10.4m telescope in La Palma that will be commissioned in the early 2017. MEGARA will allow observing up to 100 objects in a region of 3.5' x 3.5' . In its actual configuration,the MEGARA Control System has the capability to interchange between 11 Volume Phase Holographic (VPH) gratings placed on a large wheel, It integrates a state of the art Fiber-MOS system composed by 184 interconnected micro motors moving jointly mini-bundles of fibers to match the desired spatial configurations and a Data Acquisition System that images simultaneously the 600+ fibers spectra over the required spectral range.

9908-323, Session PS5

Stray light assessment and mitigation for the DESI front-end optical system

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The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14000 sq deg will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs. We will describe modeling and mitigation of stray light within the front end of DESI, consisting of the Mayall telescope and the corrector assembly. This includes the creation of a stray light model, quantitative analysis of the unwanted light at the corrector focal surface, identification of the main scattering sources, and a description of mitigation strategies to remove the sources.

9908-324, Session PS5

PSF modeling by spikes simulations and wings measurements for the MOONS multi-fiber spectrograph

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Optical design of MOONS, the next generation thousand-fiber NIR spectrograph for the VLT, involves on-axis reflective collimators and cameras, thus producing beam obstruction by fiber slit and detector support. The need to control i) the effect of the diffraction spikes produced by these obstructions, ii) the detector-induced shape variation of the PSF, and iii) the intensity profile of the PSF wings, leads us to perform both simulations and lab measurements in order to optimize the spider design and to produce a reliable PSF model useful for simulate realistic raw images for testing the data reduction. Starting from the unobstructed PSF variation, as computed with ZEMAX, we numerically computed the

diffraction spikes for different spider shapes, to which we added the PSF wing profile, as measured on a sample of the MOONS grating. Finally, we implemented the PSF defocusing due to the thick detector layer (for the visible channel), and we convolved the fiber core image and the optical ghosts, thus obtaining a detailed and realistic PSF model, that we use for spectral extraction testing, cross talk estimation and sensitivity prediction.

9908-325, Session PS5

DESI focal plate mechanical integration and cooling

Andrew Lambert, Robert W. Besuner, Todd M. Claybaugh, Joseph H. Silber, Lawrence Berkeley National Lab. (United States)

The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14000 sq deg will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs. We will describe the mechanical integration of the DESI focal plate and the thermal system design. The DESI focal plate is comprised of ten identical petal assemblies. Each petal contains 500 robotic fiber positioners. Each petal is a complete, self-contained unit, independent from the others, with integrated power supply, controllers, fiber routing, and cooling services. The major advantages of this scheme are: (1) we support installation and removal of complete petal assemblies in-situ, without disturbing the others, (2) component production, assembly stations, and test procedures are repeated and parallelizable, (3) a complete, full-scale prototype can be built and tested at an early date, (4) each production petal can be surveyed and tested as a complete unit, prior to integration, from the fiber tip at the focal surface to the fiber slit at the spectrograph. The ten petal assemblies will be installed in a single integration ring, which is mounted to the DESI corrector. The aluminum integration ring attaches to the steel corrector barrel via a flexured steel adapter, isolating the focal plate from differential thermal expansions. The plate scale will be kept stable by conductive cooling of the petal assembly. The guider and wavefront sensors (one per petal) will be convectively cooled by forced flow of air. Heat will be removed from the system at ten liquid-cooled cold plates, one per petal, operating at ambient temperature. The entire focal plate structure is enclosed in an insulating shroud, which serves as a thermal barrier between the heat-generating focal plate components and the ambient air of the Mayall dome, to protect the seeing.

9908-326, Session PS5

Design of the calibration unit for the WEAVE multi-object spectrograph at the WHT

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WEAVE is the next-generation spectroscopic facility for the William Herschel Telescope (WHT), offering multi-object (1000 fibres) and integral-field spectroscopy at two resolutions (R ~ 5000, 20000) over a 2-deg field of view at prime focus.

WEAVE will (mainly) provide optical follow up of ground-based (LOFAR) and space-based (Gaia) surveys. First light is expected towards the end of 2017.

Here we describe the calibration unit, which will be adapted from an existing unit for the AF2+WYFFOS spectrograph (WEAVE's precursor) at the WHT. We present the science and operational requirements for the unit, and summarise results from a thorough characterisation of current performance (e.g. intensity, stability and focal-plane coverage of illumination as a function of lamp type and wavelength). We then set out our plans for upgrading the unit and its control systems to meet the WEAVE science and operational requirements.

9908-327, Session PS5

MEGARA spectrograph mechanics and opto-mechanics in the AIV phase

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MEGARA (Multi-Espectrógrafo en GTC de Alta Resolución para Astronomía) is the future optical Integral-Field Unit (IFU) and Multi-Object Spectrograph (MOS) for the GTC 10.4m telescope. MEGARA is a fiber-fed spectrograph with two modes: a large Integral Field Units (IFU), called LCB (Large Compact Bundle), and the Multi-Object Spectroscopy (MOS) thanks to the use of a set of 92 robotic positioners that will place their corresponding 7-fiber mini-bundle within the 3.5arcmin x 3.5 arcmin FOV. The focal plane will be installed at Folded-Cassegrain F focus of the GTC. The fibers will feed the spectrograph that will be placed in the Nasmyth-A platform of the telescope. The spectrograph is placed on a 3m x 2m optical bench. MEGARA has four mechanisms: one at the pseudo-slit plane to do focus adjustment, the second one to allow exchaning between the fiber bundles of the two configurations (LCB and MOS), a third one that combines the functionality of a rotating shutter for exposure time control with the placement of an order-sorting filter for the red VPHs and, finally, a mechanism that allows the automat exchange among the 11 large pupil elements (containing Volume Phase Holograms, VPHs) that are simultaneously mounted. The Main optical elements (pseudo-slit assembly, collimator and camera) and the cryostat with the detector are located on another table (the auxiliary bench) that is 290mm above the main bench. There is an electro-mechanical actuator below the auxiliary bench that extracts the grating from the wheel and insert it in the optical path with high precision. The wheel is a stiffened and sandwiched-like Ø1530 mm 5083 aluminum alloy. The platforms that carry the VPH mounts will be made of AISI 316 L and a micro shot penning surface treatment will be applied to prevent scatter light. Their size is 449 mm long, 18 mm thick

and 249 mm wide at its maximum. Some mechanizing has been defined to reduce the weight. The mechanical mounts of the VPHS (up to 33kg weight each) are attached to the platforms with a kinematic 3 groove configuration.The actuators proposed for driving the wheel are a pair of servomotors with planetary reducers preloaded on a crossed rolled bearing gear by pinions in order to remove backlash. The actuators are made up of a servomotor with brake attached to a planetary reducer and a pinion. The control electronics shall control the preload in real time. Both servomotors include an encoder on axis.Together with a summary of the design and simulations, we present the real status of the spectrograph integration, the performance of the mechanisms and the alignment procedure.

9908-328, Session PS5

The DESI slit design: science and calibration solutions

Jürgen Schmoll, Durham Univ. (United Kingdom)

The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryonic Acoustic Oscillation technique. The spectra of 40 million galaxies over 14000 sq deg will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5000 fiber optic positioners. The fibers in turn will feed 10 broad-band spectrographs. We will describe the science, calibration and tests slits that are interchangeable to allow spectrograph quality assurance, alignment and calibration during construction and maintenance periods. While the calibration slits share the mechanical interface with the science slits, the architecture differs depending on the test slit purpose.

The science slit consists of 500 fibers in 20 blocks of 25 fibers, where the blocks follow the slit curvature. Each block consists of a parallel v-groove array with a flat antireflective window on the top. It has been shown that the deviation from a spherical slit to a slit approximating the curvature by flat blocks is compliant to the specifications on defocus and pupil position, as the small variations introduced are within the error budget. The science slit of each spectrograph can be removed and reproducibly replaced to allow exchange to one of two calibration and test slits, namely the sparsely populated slit and the flat field slit.

The sparsely populated slit has only the outer single fiber groove of each block populated, with the exception of one central block that bears the full 25 fibers. The purpose of this slit is to measure the point spread function and stray light behaviour of the spectrograph. This will help to align and verify the quality of the spectrograph optics during manufacture and enables quality monitoring during the life time of the instrument. The slit will be illuminated by an Offner system that projects the uniform output of an integration sphere onto a connector that holds the 44 fiber inputs for the slit.

The flat field slit consists of a single leaky optical fiber. Leaky fibers can mimick a continuous slit by emitting light sideways in a uniform glow. At the same time the source extension along the dispersion direction is of the same magnitude as the science slit width. The leaky fiber runs in a groove that follows the slit curvature, and both sides are fed with light from a conventional optical fiber. Hence, illuminating the input with white continuum light will allow a flat field illumination of the spectrograph system.

Both calibration slits will be portable setups consisting of a 4m long optical fiber run that passes the light source, conduit, strain relief box and slit breakout. The portability of the system enables testing of the spectrograph optics at the manufacturer and system monitoring of all ten spectrographs during the operational lifetime.

9908-329, Session PS5

SUBARU prime focus spectrograph: integration, testing and performance for the first spectrograph

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The Prime Focus Spectrograph (PFS) of the Subaru Measurement of Images and Redshifts (SuMIRe) project for Subaru telescope consists in four identical spectrographs fed by 600 fibers each. Each spectrograph is composed by an optical entrance unit that creates a collimated beam and distributes the light to three channels, two visible and one near infrared. We present here the integration process and test results of the first spectrograph channel.

The Assembly Integration and Test (AIT) plan is presented, as well as the methods, detailed processes and I&T tools we developed. We described the extensive tests and report on the performance results for the first visible red channel at LAM. We analyze the spectrograph performance by comparing the tests results with model data and specifications.

We also report on and discuss the technical difficulties that did appear during this integration phase. Finally, we detail the future integration plan for the next two years: the four spectrograph modules, each including the three spectral channels and their integration at the SUBARU telescope.

9908-330, Session PS5

SAMOS: a versatile multi-object-spectrograph for the GLAO system SAM at SOAR

Massimo Robberto, Space Telescope Science Institute (United States) and Johns Hopkins Univ. (United States); Megan Donahue, Michigan State Univ. (United States); Zoran Ninkov, Rochester Institute of Technology (United States); Stephen A. Smee, Robert H. Barkhouser, Johns Hopkins Univ. (United States); Mario Gennaro, Space Telescope Science Institute (United States); Andrei Tokovinin, Cerro Tololo Inter-American Observatory (Chile)

Following the advent of LSST there will be enormous pressure on 4m class telescopes for immediate followup and long-term monitoring of transients. The 4.1-m SOAR telescope can play a key role in this field, especially with its laser-guided Adaptive Optics Module (SAM) that routinely delivers images with FWHM <0.5" (frequently ~0.32") over a uniquely large 3'x3' field of view. To exploit this platform we have conceived SAMOS, a Micro-Electro-Mechanical-System based spectrograph capable of acquiring single or multiple targets in a few seconds with extreme precision. SAMOS can capture R~2,000-2,500 spectra with nominal 0.33" slit width in the 3,500-9,500 Angstrom spectral range reaching in 3600 s median SNR=5 at AB=22.9 with the red grating and 23.5 with the blue grating, comparable to 8-m class telescopes working in seeing limited conditions. In this contribution we present the SAMOS opto-mechanical design, concept of operation and provide a few examples of compelling science programs that can uniquely benefit from SAMOS sensitivity, angular resolution, versatility and simplicity of use.

9908-331, Session PS5

4MOST metrology system optical and mechanical design

Samuel C. Barden, Allar Saviauk, Roland Winkler, Leibniz-Institut für Astrophysik Potsdam (Germany)

The 4-metre Multi-Object Spectroscopic Telescope (4MOST) instrument uses ~2400 individually positioned optical fibres to couple the light of targets into its spectrographs. The fibre positioner is mounted at the Cassegrain focus of the VISTA telescope and is based on the Echidna tilting spines concept. The fibres are located in a hexagon-like structure with a diameter of 535 mm and cover a corresponding field of view on the sky with a linear diameter of 2.5 deg. Fibres are positioned relative to fixed fiducial fibres that are assumed to be very stable. Aligning the fibres with the sky is done by the pointing model for 4MOST.

The metrology system determines the position of the fibres on the focal surface of the telescope relative to the fiducial fibres. The location of the fibres needs to be measured to better than 5 micron (3 sigma). We assume that it is possible to determine the centroid of a fibre image to 1/15th of a pixel (3sigma). Four imaging cameras are mounted on the on the VISTA spider vanes. The cameras look through the entire optical train, including primary, secondary and the WFC/ADC unit. Narrow band light is illuminated through each fibre probe by a back illumination system located at the spectrograph slit. The light from the ~2400 science fibres and ~20 fiducial fibres is imaged by the metrology cameras. The software (see related paper) extracts the profiles and determines the centroids for each fibre image such that the position of the fibre can be measured to ~5 microns (~0.08 arc-sec) at the 4MOST focal surface.

We present the optical and mechanical designs of the metrology cameras and the design of the back illumination system.

9908-332, Session PS5

DESI fiber positioner performance verification

Michael S. Schubnell, Univ. of Michigan (United States); Robert W. Besuner, Parker Fagrelius, Joseph H. Silber, Lawrence Berkeley National Lab. (United States); Fransheska Berrios, Irena Gershkovich, Gregory Tarlé, Univ. of Michigan (United States)

The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14,000 square degrees will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5,000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs. The fiber positioner system, composed of 5,000 10mm diameter robotic arms, is designed to be able to position all fibers on target in less than 120 seconds with an accuracy of better than 5 microns. We will describe the qualification of the fiber positioners following assembly to verify the micron level position accuracy. Positioner production is planned at a rate of between 25 and 30 positioners per day and will be followed by immediate inspection and positioning accuracy verification. A quality control test set-up has been designed and built. This set-up will allow to control and measure 15 positioners concurrently. A Python based software package communicates with the positioners through a CAN bus, controls a fiber view camera and performs calibration and accuracy measurements. We will describe the set-up, performance characteristics and show results from pre-production tests.

9908-333, Session PS5

Visible camera cryostat design and performance for the SuMIRe Prime Focus Spectrograph (PFS)

Stephen A. Smee, Johns Hopkins Univ. (United States); James E. Gunn Sr., Princeton Univ. (United States); Mirek Golebiowski, Johns Hopkins University (United States); Stephen C. Hope, Johns Hopkins Univ. (United States); Craig P. Loomis, Princeton Univ. (United States); Robert H. Barkhouser, Johns Hopkins Univ. (United States); Michael A. Carr, Princeton Univ. (United States); Murdock Hart, Johns Hopkins Univ. (United States); Naoyuki Tamura, Atsushi Shimono, Kavli Institute for the Physics and Mathematics of the Universe (Japan); Naruhisa Takato, Subaru Telescope, National Astronomical Observatory of Japan (Japan)

We describe the design and performance of the SuMIRe Prime Focus Spectrograph (PFS) visible camera cryostats. SuMIRe PFS is a massively multi-plexed ground-based spectrograph consisting of four identical spectrograph modules, each receiving roughly 600 fibers from a 2394 fiber robotic positioner at the prime focus. Each spectrograph module has three channels covering wavelength ranges 380 nm – 650 nm, 650 nm – 940 nm, and 940 nm – 1.26 um, with the dispersed light being imaged in each channel by a f/1.07 vacuum Schmidt camera. The cameras are very large, having a clear aperture of 300 mm at the entrance window, and a mass of ~ 250 kg. Visible channel cameras utilize a pair of Hamamatsu 2K x 4K edge-buttable CCDs with 15 um pixels to form a 4K x 4K array. In this design, the camera cryostat supports the camera optics in addition to providing the vacuum space and cooling for the detector array. A single Stirling-cycle cryo-cooler from Sunpower is used to provide the cooling, a choice that was driven by the desire for high lift performance, low ambient heat dissipation, and high reliability. To mitigate cooler vibration, an active-damping control system provided by Sunpower is used. In this paper we describe the design of the cryostat and discuss various aspects of cryostat performance, including thermal performance and dynamic response.

9908-334, Session PS5

EMIR electronics AIV and commisioning

Miguel Núñez Cagigal, Enrique Joven Álvarez, Carmen Marillai Barreto Cabrera, Jesús Patrón Recio, Francisco Garzón López, Instituto de Astrofísica de Canarias (Spain)

EMIR is the wide field NIR imager and multiobject spectrograph being built as a common user instrument for the 10-m class GTC. EMIR detector is a Hawaii 2 with a controller from Astronomical Resesarch Camera and home made firmware. EMIR has several cryogenics mechanism: Multi Object Slits for 55 slits, Detector translation unit in x, y and Z axis, filters wheel and grism wheels. It has 3 electrónics cabinets including a PLC controlling the vacuum pumps and the 4 helium closed cycle cold heads. In this paper it is described the adjustments, modifications and lessons learned related to electronics for all these subsystems during the AIV stages and the commissioning in the GTC.

9908-335, Session PS5

4MOST: the high-resolution spectrograph

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(Germany); Peter Buschkamp, Max-Planck-Institut für extraterrestrische Physik (Germany); Carmen Feiz, Andreas Quirrenbach, Holger G. Mandel, Landessternwarte Heidelberg (Germany); Allar Saviauk, Leibniz-Institut für Astrophysik Potsdam (Germany)

4MOST (4-meter Multi-Object Spectroscopic Telescope) is a wide-field, fiber-feed, high-multiplex spectroscopic survey facility to be installed on the 4-meter ESO telescope VISTA in Chile. It consists of two identical low resolution spectrographs and one high resolution spectrograph. The instrument is presently in the preliminary design phase (review May 2016) and is expected to get operational end of 2020.

The high resolution spectrograph described in the paper will afford simultaneous observations of up to 820 targets - over a hexagonal field of view of ~ 4.1 degrees on sky - with a spectral resolution R>18,000 covering a wavelength range from 392 to 681nm in three channels. The athermal design of the three cameras as well as the fiber-feed exit with respect to the collimator allow a very stable spectral format on the detectors over the full operational temperature range rendering an active thermal control unnecessary.

The optical bench is mounted atop a central support structure inside a passive thermal insulation via attachment points that serve as thermal insulators and vibrational dampers.

The support structure mounts to the VISTA telescope front side below the telescope chamber's azimuth floor. Thus the fiber bundle coming from the telescope enters the spectrograph through the floor and the instrument's top cover via a service port. On the support frame's bottom side, the detector electronics and vacuum pump systems are attached, making it easy to service and install the HRS as an integrated component.

Both, the optical and mechanical design of the high resolution spectrograph are presented in detail in this paper. The expected optical performance including the highly multiplexed fiber slit concept will be given and compared to the specifications.

The thermal and finite element analyses and the resulting stability of the spectrograph under operational conditions will be shown.

The mechanical layout of the optics mounts as well as the passive thermal insulation system will be shown.

The further schedule of the 4MOST high resolution spectrograph will be outlined.

9908-336, Session PS5

4MOST metrology system image processing

Roland Winkler, Samuel C. Barden, Allar Saviauk, Leibniz-Institut für Astrophysik Potsdam (Germany)

The 4-metre Multi-Object Spectroscopic Telescope (4MOST) instrument uses ~2400 individually positioned optical fibres to couple the light of targets into its spectrographs. The fibre positioner is mounted at the Cassegrain focus of the VISTA telescope and is based on the Echidna tilting spines concept. The fibres are located in a hexagon-like structure with a diameter of 535 mm and cover a corresponding field of view on the sky with a linear diameter of 2.5 deg. Fibres are positioned relative to fixed fiducial fibres that are assumed to be very stable. Aligning the fibres with the sky is done by the pointing model for 4MOST.

The metrology system determines the position of the fibres on the focal surface of the telescope relative to the fiducial fibres. The location of the fibres needs to be measured to better than 5 micron (3-sigma) in the focal surface, approximately 0.08 arc seconds on sky. We assume that it is possible to determine the centroid of a fibre image to 1/15th of a pixel (3-sigma). Four imaging cameras are mounted on the on the VISTA spider vanes that look through the entire optical train, including primary, secondary and the WFC/ADC unit. Narrow band light is illuminated through each fibre probe by a back illumination system located at the spectrograph slit. The light from the ~2400 science fibres and ~20 fiducial fibres is imaged by the metrology cameras. The software extracts the profiles and determines the centroids for each fibre image.

This paper is focused on the image processing aspect of the metrology system, the opto-mechanical aspects are discussed in (4MOST Metrology System Optical and Mechanical Design, submitted this SPIE 2016 conference).

To assure a good sampling, we artificially broaden the fibre images to a FWHM size between 2.5 and 3 pixels. For centroiding, a gaussian profile is fitted to the fibre images, which very similar to the core profile of the fibres images. It is expected that the metrology system has to deal with a variety of different effects that can cause errors in the centroiding procedure, sorted into three categories:

Static effects that can be mitigated by calibration: CCD pixel responds, optical aberrations, CCD pixel layout (pixel locations on CCD), fiducial spine inaccuracies, calibration target errors.

Dynamic errors that change over time, but are quite predictable given the correct information: Cassegrain rotation, nonuniform refraction index of optical elements in the WFC/ADC, plate scale due to heat, WFS errors, ADC offsets and spectral spot broadening, fibre tilt, spot brightness variations, ghosts and background light.

Random effects are not precisely predictable but should be characterizable in terms of probability distribution and magnitude: pixel noise (dark current, photon noise, readout noise), pixel responds degradation, spectral freckles, dirt on lenses and detector, dome seeing, temperature gradients, back-illumination wavelength shifts, fibre mode pattern inaccuracies, coordinate transformations algorithm errors.

In this paper, we describe how we plan to counter the mentioned effects and how we want to achieve the goal of 5 microns, 3 sigma centroiding accuracy. We also present the results from our 1 in 10 scale prototype, build in our lab.

9908-337, Session PS5

The DESI fiber positioner system *(Invited Paper)*

Gregory Tarlé, Michael S. Schubnell, Jon Ameel, Curtis Weaverdyck, Irena Gershkovich, Univ. of Michigan (United States); Henry D. Heetderks, Joseph H. Silber, Robert W. Besuner, Lawrence Berkeley National Lab. (United States)

The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14,000 sq deg will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5,000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs. We will describe the fiber positioner system, composed of 5,000 10mm diameter robotic arms, designed to be able to position all fibers on target in less than 120 seconds with an accuracy of better than 5 microns. The positioners have eccentric axis kinematics. Actuation is provided by two 4 mm diameter DC brushless gearmotors. An electronics board attached to the rear accepts a DC voltage for power and CAN messages for communications and then drives the two motors. The positioner accepts the ferrulized and polished science fiber and provides a mechanically safe path through its internal mechanism. Accuracy and lifetime tests were performed.

9908-338, Session PS5

Detector and control system design and performance for the SuMIRe prime focus spectrograph (PFS) cameras

James E. Gunn Sr., Princeton Univ. (United States); Stephen A. Smee, Johns Hopkins Univ. (United States); Roger E. Fitzgerald, Fitzgerald Engineering, Inc. (United States); Murdock Hart, Stephen C. Hope, Johns Hopkins Univ. (United States); Craig P. Loomis, Princeton Univ. (United States); Grant O. Peacock, Johns Hopkins Univ. (United States); Naoyuki Tamura, Atsushi Shimono, Kavli Institute for the Physics and Mathematics of the Universe (Japan); Naruhisa Takato, National Astronomical Observatory of Japan (Japan)

We discuss the design, construction, and performance of the detector system for the SuMIRe Prime Focus Spectrograph (PFS). SuMIRe PFS is a massively multi-plexed ground-based spectrograph consisting of four identical spectrograph modules, each receiving roughly 600 fibers from a 2394 fiber robotic positioner at the prime focus. Each spectrograph module has three channels covering wavelength ranges 380 nm – 650 nm, 650 nm – 940 nm, and 940 nm – 1.26 um, with the dispersed light being imaged in each channel by a f/1.07 vacuum Schmidt camera. In this paper we describe the CCD system for the two visible channels and the overall control and data acquisition systems for the cameras, and discuss the test system for detector characterization. This system will also serve for testing the H4RG infrared detectors for the near IR channel. The first red system, utilizing a 200-micron thick fully depleted p-channel Hamamatsu CCD, is finished and has been tested. The performance is excellent, with low noise, high CTE, and very good low-level and overall linearity.

The test system uses essentially all the `flight' electronics and power supplies, in an effort to assess performance in an environment as nearly like the one to be seen in operation as possible.

9908-339, Session PS5

MEGARA: collimator and camera opto-mechanics; integration and verification strategy

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MEGARA is the new generation integral and multi-object optical spectrograph for Gran Telescopio Canarias. The whole camera and collimator opto-mechanics of the MEGARA spectrograph stands out, among other things, for the extent of its dimensions. In order to maintain the optical components constrained, so that they remain within tilt and decentration budgets, the diameters of both the mechanical housings and the optics itself have been specified in such a way that every pair of concentric mating-surfaces be manufactured by converging to the same nominal diameter, and therefore, by allowing the assembly-process be achieved at the expense of tight radial-clearances, standardized along with a narrow margin of manufacturing error. Such margin will be constrained by the ISO system of limits and fits-tolerances under the category of a "sliding fit" assembly (the H7/g6 designation according to the standard nomenclature). So, while the dimension of the involved diameters spans from 110 to 307 mm, the range of allowed radial-clearances spans from 10 to 100 microns, which makes the assembly process complicated if, additionally, the mass and structural brittleness of the lenses are considered. Here we present a detailed description of the strategy we will follow for integrating, and verifying, the MEGARA's collimator and camera opto-mechanics. The AIV process will be carried out at the INAOEs facilities, in México, with a custom designed mechanical set-up. The mechanical device manufactured to assist the integration is presented, along with a description of the difficulties overcome, and the dimensional verification procedure we will follow along with the assembly of the opto-mechanics.

9908-340, Session PS5

Development of the fibre positioning unit of MOONS

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The Multi-Object Optical and near-Infrared Spectrograph (MOONS) will exploit the full 500 square arcmin field of view offered by the Nasmyth focus of the Very Large Telescope and will be equipped with two identical triple arm cryogenic spectrographs covering the wavelength range 0.64μm-1.8μm, with a multiplex capability of over 1000 fibres. Each spectrograph will produce spectra for 500 targets simultaneously, each with its own dedicated sky fibre for optimal sky subtraction. The system will have both a medium resolution (R~4000-6000) mode and a high resolution (R~20000) mode.

The fibres positioning units are used to position each fibre independently in order to pick off each sub field of 1.0" within a circular patrol area of ~85" on sky (50mm physical diameter). The nominal physical separation between FPUs is 25mm allowing a 100% overlap in coverage between adjacent units. The design of the fibre positioning units allows parallel and rapid reconfiguration between observations. The geometry is such that pupil alignment is maintained over the patrol area.

This paper presents the design of the Fibre Positioning Units at the preliminary design review and the results of verification testing of the advanced prototypes.

Submit: MOONS will be a fibre-fed, optical to near-infrared multi-object spectrograph designed to utilise the full 25 arc minute field of view and with a multiplex capability of over 1000 fibres. The fibres will make the link between the focal plane and the two spectrographs.

9908-341, Session PS5

Very fast transmissive spectrograph designs for highly multiplexed fiber spectroscopy

Will Saunders, Australian Astronomical Observatory (Australia)

The increasing multiplex factor and resolution requirements of wide-field spectroscopic telescopes means that instrument costs are usually dominated by the spectrographs. For most projects, cost, resolution and read-noise considerations all drive camera speeds to be as fast as practicable. A simple highly efficient, fully transmissive spectrograph design is presented, which depends heavily on Calcium Fluoride aspheres, which are now routinely available via diamond turning with MRF post-polishing. For the proposed Hector instrument on the AAT, a 3-armed design with F/1.4 cameras and 4Kx4K detectors is presented. The largest optical apertures are 225mm, and the rms radii < 9microns for all wavelengths and slit positions. For larger telescopes such as the proposed Mauna Kea Spectroscopic Explorer, even faster cameras are desirable. By using existing curved detectors, the design can be pushed to F/1, while retaining excellent throughput and image quality.

9908-342, Session PS5

The Dark Energy Spectroscopic Instrument (DESI) spectrographs

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The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe by observing the spectra of 40 million galaxies over the five-year life of the project. DESI, to be installed on the Mayall 4-m telescope at KPNO in 2018, includes a new, 8 square degree field-of-view corrector at prime focus that simultaneously delivers target flux to 5,000 optical fibers, each driven by a robotic positioners. Groups of 500 fibers are fed to one of 10 high-throughput spectrographs that each covers a 360–980 nm pass band. Dichoric filters divide the pass band into three simultaneous spectral channels that each contains a transmission diffraction grating and a camera system. The spectrograph delivers a spectral resolutions reaching R = 4000. The DESI spectrograph and cameras represent a substantial advance in highly efficient, wide-field optical design. We review the performance, design and plan for the DESI spectrograph system, highlighting essential subsystems and elements of these instruments. Plans for and progress of the fabrication and testing of the spectrographs are described.

9908-343, Session PS5

The Dark Energy Spectroscopic Instrument (DESI) guide, focus and alignment system

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The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14000 sq deg will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs. We describe the Guide, Focus and Alignment (GFA) cameras designed for DESI. These cameras, as titled, will keep DESI in focus, optically aligned and guided to stay on target. We discuss design considerations, current status and construction of the first GFA camera in support of the proto-DESI effort in late 2016.

9908-344, Session PS5

Building BATMAN: a new generation spectro-imager on TNG telescope

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Next-generation infrared astronomical instrumentation for ground-based and space telescopes could be based on MOEMS programmable slit masks for multi-object spectroscopy (MOS). This astronomical technique is used extensively to investigate the formation and evolution of galaxies.

We are developing a 2048x1080 Digital-Micromirror-Device-based (DMD) MOS instrument to be mounted on the Galileo telescope (TNG) and called BATMAN. A two-arm instrument has been designed for providing in parallel imaging and spectroscopic capabilities. The field of view (FOV) is 6.8 arcmin x 3.6 arcmin with a plate scale of 0.2 arcsec per micromirror and per detector pixel. The wavelength range is in the visible and the spectral resolution is R=560 for 1 arcsec object (typical slit size). The instrument will have two 2k x 4k CCD detectors. The two arms with F/4 on the DMD are mounted on a common bench, and an upper bench supports the detectors thanks to two independent hexapods. The stiffness of the instrument is guaranteed thanks to a box architecture linking both benches. The volume of BATMAN is 1.4x1.2x0.75 m3, with a total mass of 400kg.

BATMAN will be mounted on the folded Nasmyth platform of TNG and then rotate during observation. A Finite Element Modeling (FEM) has been done under different gravity vector orientation for simulating extreme instrument locations, and the deformations of the main bench as well as translation/rotation of each detector are calculated. We reach an ultimate displacement of the center of the detectors below 20µm (i.e. <1.5 detector pixel) with respect to DMD center, for any position of the instrument on the rotator.

Hexapod have been designed, realized and delivered to LAM. They are under test for validating their ability to reach a positioning precision on the 6 degrees of freedom below 5µm. All optics have been delivered as well as fore-optics mounts, and the calibration unit including one flat field and two line lamps are under final integration. Preliminary instrument software as well as data handling philosophy have been developed. The two detectors with tilted focal planes inside the dewars have been designed, parts have been built, and they are under integration at TNG. All remaining parts including the main bench are at detailed design phase, and they will be realized during first 2016 semester.

Integration of the instrument is then scheduled during summer 2016. At this stage, we will use the experience learnt during the integration of ROBIN, a BATMAN demonstrator. ROBIN permitted to determine the instrument integration and alignment procedure, to confirm the resulting very good optical quality, both on imagery and spectroscopic arms (typically with spot diagrams within one detector pixel), and to develop the scientific optimization strategy over the whole FOV.

BATMAN on the sky is of prime importance for characterizing the actual performance of this new family of MOS instruments, as well as investigating the new operational procedures on astronomical objects. This instrument will be placed on the Telescopio Nazionale Galileo at the end-2016.

9908-345, Session PS5

Fiber system design for the Dark Energy Spectroscopic Instrument (DESI)

Claire L. Poppett, Jerry Edelstein, Space Sciences Lab. (United States); Jürgen Schmoll, David G. Bramall, Ray M. Sharples, Durham Univ. (United Kingdom)

The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14000 sq deg will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs. We will describe the fiber systems design with specific emphasis on novel approaches and essential elements that lead to exceptional performance.

The function of the fiber system is to transmit the light from 5,000 science-targets imaged at the telescope prime focus to the spectrograph optical input. Each optical fiber, with a 107m diameter core, is terminated in a ferrule that is then mounted in a positioner arm. The fibers are collected behind the focal plane into ten groups of 500. Each group spans 38 m from the focal plane to the spectrograph room via guides, supports, strain-relieving spool boxes, and ruggedized cables. Each group of 500 fibers is then precisely arranged and terminated into a linear arc that provides the optical entrance-slit illumination to an associated spectrograph.

The fiber run includes a fusion-splice connection near the focal plane to allow for positioner installation and to facilitate fabrication, integration and testing flow. In order to retain maximum throughput and minimize the focal ratio degradation (FRD) when connecting the fiber system, we are employing fusion splicing as opposed to mechanical connectorization. We report results from the splicing process, measuring a collimated focal ratio degradation (FRD) increase of less than 0.5 degrees for a f/3.9 input beam compared to >1 degree increase for mechanical connectors. We also show that the near field performance is not degraded after splicing. These results represent the first of their kind for a fiber-fed astronomical instrument.

The other novel aspect of the fiber system is that the input of the fibers are optically terminated via cleaving rather than polishing. The major advantage to cleaving is that the fibers can be held in ferrules with a much softer glue than is required for polishing. This results in lower stress being imparted onto the fiber which is especially important for the near field performance. In addition to the exceptional performance, this method has also proven to produce a higher yield than polishing since there are fewer variables.

9908-346, Session PS5

Optical fiber termination method for the Dark Energy Spectroscopic Instrument (DESI)

Claire L. Poppett, Jerry Edelstein, Yuzo Ishikawa, Space Sciences Lab. (United States); Parker Fagrelius, Lawrence Berkeley National Lab. (United States); Zak Meghrouni-Brown, Dartmouth College (United States)

The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14000 sq deg will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs. We will describe the method we use to optically terminate the fibers which offers many advantages over methods that have been used in the past.

In most astronomical fiber-fed instruments the fibers are terminated via bonding in a ferrule and then polishing with progressively finer grades of polishing paper and polishing solutions until the required performance is achieved. Since the fibers have to be held within the ferrules securely to withstand the relatively violent polishing process, a hard glue must be used. This introduces stress onto the end of the fiber and dominates the focal ratio degradation performance.

We have demonstrated that simply bonding cleaved fibers to glass ferrules is a more efficient alternative without sacrificing fiber performance, which was determined by measuring the focal ratio degradation (FRD). In this study we found that by minimizing the FRD contributions from the fiber-ferrule bonding and fiber cleaving, we can quickly produce high-performance fibers satisfying the DESI science requirements.

9908-347, Session PS5

The Maunakea Spectroscopic Explorer: throughput optimization

Nicolas Flagey, Canada-France-Hawaii Telescope (United States); Shan B. Mignot, Observatoire de Paris à Meudon (France); Kei Szeto, Alan McConnachie, Rick Murowinski, Canada-France-Hawaii Telescope (United States)

The Maunakea Spectroscopic Explorer (MSE) will each year obtain millions of spectra in the optical to near-infrared, at low (R~2,500) to very high (R~40,000) spectral resolution by obtaining ~3000 spectra per pointing via a highly multiplexed fiber-fed system. Key science programs for MSE include black hole reverberation mapping, stellar population analysis of faint galaxies at high redshift, and sub-km/s velocity accuracy for stellar astrophysics. Most science objectives require observations of faint Galactic (visual magnitudes up to 20) and very faint extra-galactic targets (visual magnitudes up to 24). As a consequence, MSE will need to achieve the highest throughput possible over a spectral range that extends from 360 to 1800 nm. In this paper, we present the different components that affect the throughput, from the atmosphere to the detectors, and the technical solutions we are considering to optimize the overall throughput of the project and meet the science requirements.

9908-66, Session 14

Cosmological surveys with multi-object spectrographs *(Invited Paper)*

Matthew M. Colless, The Australian National Univ. (Australia)

Multi-object spectroscopy has been a key technique contributing to the current era of 'precision cosmology'. From the first exploratory surveys of the large-scale structure and evolution of the universe to the current generation of superbly detailed maps spanning a wide range of redshifts, multi-object spectroscopy has been a fundamentally important tool for mapping the rich structure of the cosmic web and extracting cosmological information of increasing variety and precision. This will continue to be true for the foreseeable future, as we seek to map the evolving geometry and structure of the universe over the full extent of cosmic history in order to obtain the most precise and comprehensive measurements of cosmological parameters. In this talk I will briefly summarize the contributions that multi-object spectroscopy has made to cosmology so far, then review the major surveys and instruments currently in play and their prospects for pushing back the cosmological frontier. Finally, I will examine some of the next generation of instruments and surveys to explore how the field will develop in coming years, with a particular focus on specialised multi-object spectrographs for cosmology and the capabilities of multi-object spectrographs on the new generation of extremely large telescopes.

9908-67, Session 14

Progress along the E-ELT instrumentation roadmap *(Invited Paper)*

Mark M. Casali, Suzanne K. Ramsay, European Southern Observatory (Germany)

A suite of seven instruments and associated AO systems have been planned as the "E-ELT Instrumentation Roadmap". Following the E-ELT project approval in December 2014, rapid progress has been made in organising and signing the agreements for construction with European universities and institutes. Three instruments (HARMONI, MICADO and

METIS) and one MCAO module (MAORY) have now been approved for construction. In addition, Phase-A studies have begun for the next two instruments - a multi-object spectrograph and high-resolution spectrograph. Technology development is also ongoing in preparation for the final instrument in the roadmap, the planetary camera and spectrograph.

In this talk I will give a summary of the strategies, problems and capabilities of this first set of instruments for the E-ELT, and outline the organisation of the instrumentation programme.

9908-68, Session 14

Instrumentation progress at the Giant Magellan Telescope project *(Invited Paper)*

George H. Jacoby, Rebecca A. Bernstein, GMTO Corp. (United States) and Carnegie Observatories (United States); Antonin H. Bouchez, GMTO Corp. (United States); Matthew M. Colless, The Australian National Univ. (Australia); Darren L. DePoy, Texas A&M Univ. (United States); Brady Espeland, The Australian National Univ. (Australia); Daniel T. Jaffe, The Univ. of Texas at Austin (United States); Jonathan S. Lawrence, Australian Astronomical Observatory (Australia); Jennifer L. Marshall, Texas A&M Univ. (United States); Peter McGregor, Robert Sharp, The Australian National Univ. (Australia); Andrew Szentgyorgyi, Harvard Univ. (United States); Brian Walls, GMTO Corp. (United States)

Instrument development for the 24 m Giant Magellan Telescope (GMT) will be described: current activities, progress, status, and schedule. One instrument team has completed its preliminary design and is currently performing its final design (G-CLEF, an optical 350-950 nm high-resolution and precision radial velocity echelle spectrograph). A second instrument team is in its conceptual design phase (GMACS, an optical 350-950 nm low-to-medium resolution 6-10 arcmin field multi-object spectrograph). A third instrument team is midway through its preliminary design phase (GMTIFS, a near-IR YJHK diffraction-limited imager/integral-field-spectrograph), focused on risk reduction prototyping and design optimization. A fourth instrument team is currently fabricating the 5 silicon immersion gratings it needs as a critical element of its preliminary design phase (GMTNIRS, a JHKLM high-resolution AO-fed echelle spectrograph). And, another instrument team is focusing on technical development and prototyping (MANIFEST, a facility robotic multi-fiber-feed with a 20 arcmin field of view). In addition, a medium-field (6 arcmin, 0.07 arcsec/pix) optical imager has been added to support telescope and AO commissioning activities, and to provide narrow-band science imaging. In the spirit of advancing synergies with other groups, I will discuss the challenges of running an ELT instrument program, lessons learned, and opportunities for cross-ELT collaboration.

9908-69, Session 14

Thirty Meter Telescope science instruments: a status report *(Invited Paper)*

Luc Simard, Thirty Meter Telescope (United States) and National Research Council Canada (Canada); Brent L. Ellerbroek, Ravinder S. Bhatia, Thirty Meter Telescope (United States); Matthew V. Radovan, Univ. of California Observatories (United States) and Thirty Meter Telescope (United States); Eric M. Chisholm, Thirty Meter Telescope (United States)

An overview of the current status of the Thirty Meter Telescope (TMT) science instruments is presented. Work on the three first-light instruments (WFOS, IRIS and IRMS) has made significant progress in many key areas. IRIS has been re-designed end-to-end to provide an expanded imaging field of view of 34'' x 34'' that is now very well-matched to the corrected field delivered by the NFIRAOS AO system. WFOS has been the focus of a extensive set of mini-studies conducted by 15 institutes across the TMT partnership, and these mini-studies have provided many new ideas that will be included in future design phases. A very low-vibration facility cryogenic cooling system for the instruments based on gaseous helium turbine expanders has also been designed and may provide a new way to cool instruments on extremely large telescopes. Finally, many groups in TMT partner communities are developing future instruments concepts in preparation for a future call for second-generation instrument proposals.

9908-70, Session 15

The Infrared Imaging Spectrograph (IRIS) for TMT: instrument overview

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IRIS is a near-infrared (0.84 to 2.4 micron) integral field spectrograph and wide-field imager being developed for first light with the Thirty Meter Telescope (TMT). It mounts to the advanced adaptive optics (AO) system NFIRAOS and has integrated on-instrument wavefront sensors (OIWFS) to achieve diffraction-limited spatial resolution at wavelengths longer than 1 μm. With moderate spectral resolution (R ~ 4000 – 8,000) and large bandpass over a continuous field of view, IRIS will open new opportunities in virtually every area of astrophysical science. It will be able to resolve surface features tens of kilometers across Titan, while also mapping the most distant galaxies at the scale of an individual star forming region. This paper summarizes the entire design and capabilities, and includes the results from the completed preliminary design phase.

9908-71, Session 15

The E-ELT first light spectrograph HARMONI: capabilities and modes

Niranjan A. Thatte, Univ. of Oxford (United Kingdom); HARMONI Consortium, Univ of Oxford (United Kingdom)

HARMONI is the first light, visible and near-infrared integral field

spectrograph for the European Extremely Large Telescope (E-ELT). A work-horse instrument, it provides a range of spatial scales, ranging from diffraction limited to a factor of 15 coarser, coupled with a range of spectral resolving powers, ranging from R~3500 to R~20000. A “point-and-shoot” instrument, HARMONI is ideally suited for spatially resolved spectroscopy of astrophysical sources, whilst also providing ultra-sensitive point-source spectroscopy over the 0.5 to 2.45 micrometres wavelength range.

The technical specifications are now well established, and we will present a summary of HARMONI’s capabilities. Following contract signature, we have expanded the consortium’s efforts to include the HARMONI Laser Tomographic Adaptive Optics (H-LTAO) capability. During the preliminary design phase, we are exploring telescope-instrument interface architectures that will allow seeing limited observing at visible and near-IR wavelengths, as well as bright natural guide star (SCAO) and H-LTAO adaptive optics assisted observing at near-infrared wavelengths. We will also discuss baseline solutions that support all these observing modes and optimal performance.

9908-72, Session 15

GMTIFS: The Giant Magellan Telescope integral fields spectrograph and imager

Rob Sharp, Gabriel J. Bloxham, Robert Boz, David Bundy, John Davies, Brady Espeland, John Hart, Jon Nielsen, Colin Vest, Annino Vaccarella, Peter J. Young, Peter McGregor, The Australian National Univ. (Australia)

GMTIFS is to be the first-light adaptive optics spectrograph for the GMT, having been selected as a first generation instrument through a competitive review process in 2010. The GMTIFS concept is for a workhorse single-object integral field spectrograph, operating at intermediate resolution (R~5,000 & 10,000) with a parallel imaging channel. The IFS offers variable spaxel scales to Nyquist sample the diffraction limited GMT PSF from ? ~ 1-2.5 ?m as well as a 50 mas scale to provide high sensitivity for low surface brightness objects. GMTIFS will operate with all AO modes of the GMT (Natural guide star - NGSAO, Laser Tomography – LTAO, and, Ground Layer - GLAO) with a strong emphasis on achieving high sky coverage for LTAO observations. We summarize the principle science drivers for GMTIFS, the major design concepts that allow these goals to be achieved, and the principle challenges being addressed in the preliminary design study (via prototyping) to ensure GMTIFS meets its ambitious specification.

9908-73, Session 15

MICADO: first light imager for the E-ELT

Richard Davies, Max-Planck-Institut für extraterrestrische Physik (Germany); João Alves, Univ. Wien (Austria); Yann Clénet, Observatoire de Paris à Meudon (France); Florian Lang-Bardl, Ludwig-Maximilians-Univ. München (Germany); Harald Nicklas, Georg-August-Univ. Göttingen (Germany); Roberto Ragazzoni, INAF - Osservatorio Astronomico di Padova (Italy); Josef Schubert, Eckhard Sturm, Max-Planck-Institut für extraterrestrische Physik (Germany); Eline Tolstoy, Univ. of Groningen (Netherlands)

MICADO, the Multi-AO Imaging Camera for Deep Observations, will equip the E-ELT with a first light capability for diffraction limited imaging at near-infrared wavelengths. The instrument is optimised to work with a 1arcmin field corrected by the laser guide star multi-conjugate adaptive optics module MAORY, but it also includes a simple and robust natural guide star wavefront sensor for single-conjugate adaptive optics. And it will be able to function in a “stand-alone” mode that involves operating with the SCAO wavefront sensor but without MAORY. The instrument’s observing modes focus on various flavours of imaging, including astrometric, high contrast, and time resolved. There is also a single object spectroscopic mode optimised for wavelength coverage at moderately high resolution. In this contribution, we begin by outlining the scientific rationale for the observing modes. We then describe the design of MICADO, and explain how it has been developed to fulfil the science requirements, as well as meet the observatory operational and maintenance requirements.

9908-74, Session 15

Status of the mid-infrared E-ELT imager and spectrograph METIS

Bernhard R. Brandl, Leiden Univ. (Netherlands) and Technische Univ. Delft (Netherlands); Roy van Boekel, Max-Planck-Institut für Astronomie (Germany); Sascha P. Quanz, ETH Zürich (Switzerland); Rieks Jager, Nederlands Centrum voor Laser Research B.V (Netherlands); Markus Feldt, Max-Planck-Institut für Astronomie (Germany); Alistair C. H. Glasse, UK Astronomy Technology Ctr. (United Kingdom); Manuel Güdel, Univ. Wien (Austria); Michael R. Meyer, ETH Zürich (Switzerland); Eric J. Pantin, CEA-Ctr. de SACLAY (France); Christoffel Waelkens, KU Leuven (Belgium)

METIS is one the first three instruments on the E-ELT, expected to see first light in 2025. Apart from diffraction limited imaging, METIS will provide coronagraphy and medium resolution slit spectroscopy over the 3 - 19um range, as well as high resolution (R ~ 100,000) integral field spectroscopy from 2.9-5.3μm, including a mode with extended instantaneous wavelength coverage. The unique combination of these observing capabilities, makes METIS the ideal instrument for the study of circumstellar disks and exoplanets. Additional science topics include our Solar system, the Galactic center, brown dwarfs, evolved stars, massive stellar clusters, active galactic nuclei (AGN), local starbursts, transient events, and luminous infrared galaxies at intermediate redshift. In this paper we provide an update of the relevant science drivers, together with simulated science observations. We discuss the programmatic status and present a preliminary design of the instrument. The latter will focus on the areas of the revised optical design, the adaptive optics concept, data reduction pipeline, and the challenges with regard to calibration of observations at thermal infrared wavelengths on a six-mirror ELT.

9908-75, Session 15

GMTNIRS: progress toward the Giant Magellan Telescope near-infrared spectrograph

Daniel T. Jaffe, The Univ. of Texas at Austin (United States); Stuart I. Barnes, Leibniz-Institut für Astrophysik Potsdam (Germany); Cynthia B. Brooks, Hanshin Lee, Gregory Mace, The Univ. of Texas at Austin (United States); Soojong Pak, Kyung Hee Univ. (Korea, Republic of); Byeong-Gon Park, Chan Park, Korea Astronomy and Space Science Institute (Korea, Republic of)

GMTNIRS is a first-generation instrument for the Giant Magellan Telescope. It is a high-resolution spectrograph that will cover the 1.15-5.5 ?m range in a single exposure with R=?/??= 60,000 in the J, H, and K bands and R=85,000 in the L and M bands. It resides on the rotating instrument platform and employs the facility adaptive optics system. GMTNIRS design

is evolving in response to lessons from its highly successful forerunner instrument, IGRINS. These lessons include the utility of an infrared slit viewing camera, the need to consider extended targets in the science plan, the importance of precise and straightforward wavelength calibration in all observing windows, and the value of a simple-to-use pipeline that produces science-ready data products. Technical changes are also driving evolution of the design. It has proven impractical to manufacture quality 200mm long immersion gratings at the necessary precision. The success of primary mirror phasing efforts has removed the need for a very wide entrance slit that would have been needed to accommodate the Airy pattern of individual segments. The high efficiency of our double-side coated JWST grisms introduces the possibility of transmissive cross-dispersers at L and M. These changes move us toward a design with almost the same R (see above) as presented in our previous work but with a much more compact physical envelope. We will report on the optimization of the instrument design with these technical changes in mind. We are also producing the critical Si immersion gratings. The grating production is well under way and includes manufacture of H and K gratings and process development for the precision needed in the J band and for the manufacture of larger gratings for the L and M band. The development of GMTNIRS is on track with the results from IGRINS and the progress in the lab giving us substantial assurance that the new instrument can meet its performance goals.

9908-76, Session 16

The GMT-Consortium Large Earth Finder (G-CLEF): an optical Echelle spectrograph for the Giant Magellan Telescope (GMT)

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The GMT-Consortium Large Earth Finder (G-CLEF) will be a cross-dispersed, optical band echelle spectrograph to be delivered as the first light scientific instrument for the Giant Magellan Telescope (GMT) in 2021. G-CLEF is vacuum-enclosed and fiber-fed to enable precision radial velocity (PRV) measurements, especially for the detection and characterization of low-mass exoplanets orbiting solar-type stars. The passband of G-CLEF is very broad, extending from 3500Å to 9500Å. This passband provides good sensitivity at blue wavelengths for stellar abundance studies and deep red response so as to permit observations of high-redshift phenomena.

The design of G-CLEF incorporates several novel technical innovations and methodologies when compared with previous PRV instruments and instrumentation for ground based telescopes in general. G-CLEF has recently passed preliminary design review (PDR) and a subsequent gate review of the spectrograph optical design. In this paper we give an overview of the innovative features of the post-PDR design; detailed discussion of these are provided in other submissions to these proceedings (Baldwin et al., Ben-Ami et al., Evans et al., Mueller et al., Oh, et al.).

In particular, G-CLEF will be the first PRV spectrograph to have a composite optical bench to exploit that material's extremely low coefficient of thermal expansion and high stiffness-to-mass ratio. The design also incorporates a unique thermal control system design that maximizes instrumental immunity to ambient temperature fluctuations. This system has been prototyped and has demonstrated sub-millikelvin thermal stability on diurnal time scales.

The spectrograph camera subsystem is divided into a red and a blue channel, split by a dichroic beamsplitter, so there are two independent refractive spectrograph camera designs. These designs minimize lens fabrication risk while maximizing performance as measured by point spread function size, throughput and immunity from ghosting and scattered light. The exposure meter has been implemented as a subsystem of the camera and harvests out-of-order light at the volume phase holographic gratings, which cross-disperse the two spectrograph beams after the dichroic.

The control system software is being developed in model-driven software context that has been adopted globally at the GMT for all telescope systems. We discuss control software as well as other G-CLEF software, prominently the reduction pipeline.

G-CLEF has been conceived and designed within a strict systems engineering framework. As a part of this process, we have developed a powerful tool set to assess the predicted performance of G-CLEF as it has evolved through subsequent design phases.

In addition to discussing these innovations, we review the design status of major subsystems, especially the telescope interface and flexure control system, the optical fiber feed for the spectrograph, the calibration system and the interface to the multi-object spectroscopy feed (MANIFEST) being developed by the Australian Astronomical Observatory.

9908-77, Session 16

HIRES the high-resolution spectrograph for the E-ELT

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The current E-ELT instrumentation plan foresees a High Resolution Spectrograph conventionally indicated as HIRES whose Phase A study will start in 2016. Such an instrument is capable of providing unique breakthroughs in the fields of exoplanets, star and planet formation, physics and evolution of stars and galaxies, cosmology and fundamental physics.

A consortium composed of institutes and organizations from many ESO member states has conducted a preliminary scientific and technical study of a modular instrument able to provide high-resolution spectroscopy (R~100,000) in a wide wavelength range (0.37-2.5 μm).

We will present the technical solutions envisaged by the HIRES consortium and an outline of the many exciting science cases that the use of HIRES at the E-ELT will allow to address.

ADDITIONAL AUTHORS TO BE ADDED LATER FOR CURRENTLY MISSING INFO: C. Allende Prieto, A. Basden; X. Bonfils, D. Buscher, A. Cabral, I. De Castro Leao, P. Figueira; B. Gustafsson; K. Heng; D. Henry; O. Kochukhov; G. Israelian; H. Mandel, M. Monteiro; T. Morris; G. Murray; P. Noterdaeme; I. Parry, P. Petitjean; T. Puzia; J. L. Rasilla, P. Rees; E. Stempels; M. Wells; F. Wildi; M. Zoccali

9908-78, Session 16

MOSAIC: the E-ELT multi-object spectrograph

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The MOSAIC case draws on all fields of contemporary astronomy. When combined with the unprecedented sensitivity of the E-ELT, MOSAIC will be the world unique MOS facility having both multiplex and multi-IFU capability.

We argue that the most compelling and competitive cases for ELT science demand such a capability as soon as possible. MOS observations in the early stages of E-ELT operations will be essential for follow-up of sources identified by the JWST. In particular, multi-object adaptive optics and accurate sky subtraction with fibers have both recently been demonstrated on sky, making fast-track development of MOSAIC feasible.

In this paper I'll review the preliminary results of the Phase A, including the scientific, technical and managerial aspects of MOSAIC.

9908-79, Session 16

The Giant Magellan Telescope multi-object astronomical and cosmological spectrograph (GMACS)

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We review the latest conceptual design for a moderate resolution optical spectrograph for the Giant Magellan Telescope (GMT). The spectrograph is designed to make use of the large field-of-view of the GMT and be suitable for observations of very faint objects across a wide range of wavelengths. We summarize important science drivers and present the technical specifications for the instrument. Other papers at this conference will present more details of the mechanical and optical design.

9908-80, Session 16

The wide-field optical spectrometer for TMT

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The Wide Field Optical Spectrometer (WFOS) is the seeing-limited, visible-wavelength imaging multiobject spectrograph (MOS) planned for first-light use on the Thirty Meter Telescope (TMT). The WFOS project is an international collaboration between the TMT partners in the USA, Japan, China and India and is being led by the University of California Observatories at UC Santa Cruz.

WFOS will provide 0.2 arc sec image quality and high throughput (>30%) over a 40.5 square arc minute field of view with a spectral resolution of 500 to 5000 for a 0.75 arc second slit. Wide wavelength coverage (310-1000 nm) is accomplished with two color channel sharing a common collimator.

We report here on developments since 2014 related to the optical and mechanical design to improve the flexure performance of this extremely large Nasmyth instrument on the 30 meter TMT.

9908-348, Session PS6

Study of the impact of E-ELT wavefront errors residuals on the MICADO astrometric observations

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The paper describes an end-to-end optical simulation developed using commercial ray tracing software that allows studying the effect of the E-ELT telescope instabilities on the Multi-AO Imaging Camera for Deep Observations (MICADO). The primary goal and observing mode of MICADO is imaging, with a focus on astrometry with an accuracy of about 50 ?as. To achieve this ambitious goal a careful examination of the possible statistical and systematic effects that can influence the astrometric accuracy is required. Here we concentrate on the perturbations coming from different telescope instabilities, related to high spatial frequency errors (M1 segments scale) and dynamical effects (wind and vibrations) of the E-ELT primary and secondary mirror. ESO has been developing an extended dataset of these perturbations that are integrated inside the optical model of the telescope and the instrument relay optics for gathering the aberrated wavefronts to be compensated by the adaptive optics (AO) system. The wavefront error residuals reflected off the E-ELT adaptive mirrors are then propagated inside the MICADO camera to check the distortions and the possible effects on the astrometric measurement at the instrument focal plane. This tool is conceived to get both a reliable estimate of the effect of wavefront residuals errors on the astrometric observations and to drive the calibration scheme of the instrument.

9908-349, Session PS6

GMTIFS: challenging optical design problems and their solutions for the GMT integral-field spectrograph

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GMTIFS is a first light instrument for the Giant Magellan Telescope (GMT). It is a combined Imager and Integral Field Spectrograph (IFS) designed to work with Adaptive Optics (AO) System of the GMT. Working at the diffraction limit of the GMT and satisfying the challenging AO interface requirements and constraints results in unique optical challenges. We describe several of these unique challenges and how we have solved them. The GMT has a direct feed architecture which increases transmission and reduces emissivity, however one of the major challenges is the cryostat window which must be tilted to reflect visual wavelengths to the AO system. The window must be large enough to transmit the both the central science field to the Imager and IFS, and the full 180 arcsecond diameter guide field to the on-instrument wavefront sensor. For a plane-parallel window, this tilt causes astigmatism in the transmitted beam that must be corrected. A corrective system using two plates, tilted and slightly wedged in opposite directions, is proposed. Geometry and performance of the system is described. Another challenging optical design is the anamorphic field projector. The Integral Field Unit of GMTIFS requires that a small field delivered by the telescope be projected onto an Image Slicer at much larger scale, with the magnification in the spectral direction being twice that in the spatial direction to make the spaxels square when projected onto the sky. Output images must be coincident in the spectral and spatial projections for both the field and pupil. Additionally, field and pupil image locations must be independently controllable so that they can be made coincident for interchangeable units that provide a range of output field scales. A two-mirror system that satisfies these requirements is described.

9908-350, Session PS6

MICADO: the camera support structure at the E-ELT Nasmyth focus

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MICADO is one of the first light instruments at the E-ELT and is designed to work with the MCAO system MAORY. The ability to operate in a stand-alone mode without MAORY includes an additional SCAO system. Therefore, the instrument support structure has to fulfil two purposes, the positioning of the camera in a) its stand-alone mode and b) when it will mounted underneath the MCAO facility MAORY. The structure is addressed regarding its functionality such as passive and possible active positioning of the instrument. Very first FEA results will be given as well as other performance assessments.

9908-351, Session PS6

Design of a large image derotator for the E-ELT instrument MICADO

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The Multi-AO Imaging Camera for Deep Observations (MICADO), a first light instrument for the 39 m European Extremely Large Telescope (E-ELT), is being designed and optimized to work with the Multi-Conjugate Adaptive Optics (MCAO) module MAORY (0.8-2.5 ?m) using laser guide stars. The MICADO-MAORY configuration will provide diffraction limited imaging over a large 53-arcsec field of view. During the early operational phase, MICADO will operate with its own Single-Conjugate Adaptive Optics (SCAO) system using natural guide stars, for on-axis diffraction limited performance. The MICADO consortium has started the preliminary design phase with the kick-off meeting held in Vienna, on October 7, 2015.

The current concept of the MICADO instrument consists of a structural

cryostat (2.1 m diameter and 2 m height) with the SCAO wavefront sensor (WFS) on top (cryostat + WFS ≈ 3.000 Kg). The cryostat is mounted via its central flange with a direct interface to a large 2.5-m-diameter high-precision image derotator. The whole assembly is suspended at 3.6 m above the E-ELT Nasmyth platform by a Hexapod-type support structure. The MICADO calibration unit, the relay optic components and the M7 mirror are located on a dedicated optical bench above the cryostat/SCAO-WFS assembly, mounted on an auxiliary hexapod also attached to the static mechanical interface of the derotator. The instrument electronics cabinets, the cable-wrap and the cooling system are placed on a separated coarse-precision co-rotating platform below the cryostat.

We describe the design and development of the MICADO derotator, a key mechanism that must precisely rotate the cryostat/SCAO-WFS assembly around its optical axis with an angular positioning accuracy lower than 10 arcsec, in order to compensate the field rotation due to the alt-azimuth mount of the E-ELT. This device consists of a high precision bearing, drivers, motors, encoders and very stiff mechanical interfaces. A trade-off analysis considering different bearing technologies was performed to select the most suitable one for this application. As a result, the MICADO derotator is being developed using a custom-made four-point contact ball bearing. Special attention is being given to estimate and simulate the performance of the derotator during the design phase, while both static and dynamics behaviors are being considered in parallel. The statics flexure analysis is done using a detailed Finite Element Model (FEM). The dynamics simulation is being developed with the mathematical model of the derotator implemented in Matlab/Simulink. Finally, both aspects must be combined through a realistic end-to-end model of the derotator, verifying that the concept matches the requirements. The main challenges to be handled in this project are: (i) the design of the mechanical interfaces to minimize mass, as well as the deformation and the effect of the warping moment on the bearing and, (ii) the analysis of the friction in the bearing at low tracking velocities to compensate the Stick-slip effect with a position-velocity closed-loop control system.

9908-352, Session PS6

A new test facility for the E-ELT infrared detector program

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During the development of the VLT instrumentation program, ESO acquired considerable expertise in the area of infrared detectors, their testing and optimizing their performance. This can be mainly be attributed to a very competent team and most importantly to the availability of a very well suited test facility, namely, IRATEC.

This test facility, was designed more than 15 years ago, specifically for 1K x 1K detectors such as the Aladdin device, with a maximum field of only 30 mm square. Unfortunately, this facility is no longer suited for the testing of the new larger format detectors that are going to be used to equip the future E-ELT instruments. It is projected that over the next 20 years, there will be of the order of 50-100 very large format detectors to be procured and tested for use with E-ELT first and second generation instruments and VLT third generation instruments.

For this reason ESO has initiated the in-house design and construction of a dedicated new IR detector arrays test facility: the Facility for Infrared Array Testing (FIAT). It will be possible to mount two 60 mm square detectors in the facility, as well as mosaics of smaller detectors. It is being designed to have a very low thermal background such that detectors with 5.3 um cut-off material can routinely be tested.

The paper introduces the most important use cases for which FIAT is designed: they range from performing routine performance measurements on acquired devices, optimization setups for custom applications (like spot scan intra-pixel response, persistence and surface reflectivity measurements), test of new complex operation modes (e,g, high speed sub-windowing mode for low order sensing, flexure control, etc) and the development of new tests and calibration procedures to support the scientific requirements of the the E-ELT and to allow troubleshooting the unexpected challenges that arise when a new detector system in brought online. The facility is also being designed to minimize the downtime required to change to a new detector then cool it down, ready for testing.

The status of the opto-mechanical and cryogenic design is also described in detail, with particular emphasis on the technical solutions identified to fulfill the FIAT top level requirements.

We will also describe how the FIAT project has been set-up as a training facility for the younger generation of engineers who are expected to take over the job from the experienced engineers and ensure that the lessons learnt in so many years of successful IR instrumentation projects at ESO are captured for this next generation.

9908-353, Session PS6

Science requirements and trade-offs for the MOSAIC spectrograph for the European ELT

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Building on the comprehensive White Paper on the scientific case for multi-object spectroscopy on the European ELT, we present the top-level instrument requirements that are being used in the Phase A design study of the MOSAIC concept. The assembled cases span the full range of E-ELT science and generally require observations with two modes ('high multiplex' and 'high definition') to best exploit the exciting sensitivity and spatial performance of the telescope. We will present the latest science simulations that are being used in trade-off studies to inform the capabilities of MOSAIC and the technical implementations required.

9908-354, Session PS6

The Infrared Imaging Spectrograph (IRIS) for TMT: preliminary design of image slicer

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The InfraRed Imaging Spectrograph (IRIS) is one of three first light science instruments for the Thirty Meter Telescope (TMT). It will provide dedicated imaging and integral field spectroscopic observations in parallel fed by a Narrow Field InfraRed Adaptive Optics System (NFIRAOS). The IRIS imager delivers light to a dual-channel Integral Field Spectrograph (IFS) through a

pair of pick-off mirrors in the central field. The IFS creates multi-functional ability to explore the universe in IR (0.84 – 2.4um) with moderate spectral resolution of R=4,000/8,000 and four spaxel scales of 4, 9, 25, 50 milli-arc-seconds (mas). An image slicer serves one of the two spectral channels as its Integral Field Unit (IFU) in two spaxel scales of 25 and 50mas over the continuous science field of 2.2x1.125 mas and 4.4x2.25 mas respectively. It splits the field into 88 integral field units (IFU), the images of which are linearly arranged into two parallel slits due to the detector format (4Kx4K @ 15um). A novel all-reflective design of image slicer uses a new 'brick stage' layout to make the adjacent mirrors staggered in order, and deliver close to diffraction limited image quality. The detail of the image slicer design will be presented in this paper.

9908-355, Session PS6

HIRES the high-resolution spectrograph for the E-ELT: dynamics and control of the repositioning mechanism for the E-ELT HIRES polarimeter

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A full Stokes dual channel polarimeter for the E-ELT HIRES spectrograph has been envisioned for the intermediate focus f/4.4, operating within a spectral range of 0.4-1.6 μ. It will feed the HIRES instrument located on the Nasmyth platform via two pairs of dedicated fibers: one fibre pair optimized for the BVRI, the other one optimized for the JH band or any other feasible combination. The instrument must be retractable within a workspace in fulfillment with the ESO requirements on the allocated volume and the dynamic response of the AO tower. For such purpose a swinging arm has been designed with a rotation provided by 5 revolute joints plus a jackscrew. Moreover repeatability in repositioning has to be guaranteed by a parallel manipulator, performing an alignment procedure mainly along 5 axes. Dynamics and control criteria with a feedforward chain to compensate for vibration forces and feedback chain for tracking procedure are hereafter presented.

9908-356, Session PS6

Opto-mechanical design of the G-CLEF flexure control camera system

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The GMT-Consortium Large Earth Finder (G-CLEF) is a fiber-fed, optical band echelle spectrograph that will be the first light instrument for the Giant Magellan Telescope (GMT). The G-CLEF Front End Assembly (GCFEA) including a tertiary mirror and a set of reimaging camera relays the telescope beam onto the surface of the fiber mirror installed on the GMT Instrument Platform. The light from the target object will be incident into the fiber and the outer field of 1.5 x 1.5 arcmin will be reflected to the Flexure Control Camera (FCC). The FCC is to monitor and control the local flexure of the GCFEA in order to guide the target within 7 milli-arcsec. The FCC includes a collimator made of a triplet lens, a folding mirror, a filter-wheel system housing four neutral density filters and a tent prism as focus analyzer, a reimaging camera with a pair of doublet lenses, and a CCD detector. The detector module has the features of the linear translation and field de-rotational function. We present in this study the current status of the optical and mechanical design of the FCC developed after the instrument Preliminary Design Review held in April 2015.

9908-357, Session PS6

Polishing test of a poly-crystal calcium fluoride lens: toward the development of TMT WFOS

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Wide-Field Optical Spectrograph (WFOS) is one of the first-light instruments of Thirty Meter Telescope (TMT). It offers the optical multi-slit spectroscopy and imaging functions. The project is an international collaboration led by University of California Santa Cruz. We have joined the WFOS project since 2010 and contributed on its science camera systems. WFOS divides light around 550 nm by a dichroic mirror located between the collimator and the dispersers. Each red and blue channel has the science camera system which is optimized for each wavelength range.

WFOS is the biggest instrument among the first-light ones, and the pupil image created in it is 300 mm in diameter. Therefore the science cameras need to be sufficiently large (> 400 mm) to capture light from this large pupil image. For such large camera systems, available optical glasses with high quality are very limited. One critical item is Calcium Fluoride (CaF2). CaF2 is very useful to reduce aberration, and hence many astronomical instruments use it as lens material. However large CaF2 with high quality is difficult to be manufactured. The current largest CaF2 is 440 mm in diameter. Although a mono-crystal blank with a diameter of 440 mm can be obtained at some yield, we might have to use poly-crystal depending on the funding and schedule situations. The poly-crystal blank has some internal regions with different crystal directions. Basically, CaF2 does not have an optical index dependency on the crystal direction. At the boundary between those regions, however, the optical index and the stress birefringence are different from the sounding regions. In addition, removal rate in polishing depends on the crystal direction, and hence a poly-crystal CaF2 lens is expected to have figure error after polishing. Those internal and surface possibly affect the image quality. This is one of the major risk items in the WFOS development.

To address this issue, we conducted a polishing test of a poly-crystal CaF2 lens with a diameter of 70 mm as a first step. One surface is convex with a radius of 164.74 mm and the other is flat. As expected, we found figure error around the boundary. The figure error is ~139 nm PV and ~26 nm rms. Those values themselves are not significant, but the figure error is much localized and the slop is steeper than that of the global pattern. The steeper slope makes a light ray more largely deviate from the ideal path. On the other hand, the figure error occupies a small fraction of the entire area of the lens. This invokes us a small effect on the image quality. We will carry out the Zemax simulation to study the effect.

9908-358, Session PS6

The MANIFEST prototyping design study

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MANIFEST is a facility multi-object fibre system for the Giant Magellan Telescope, which uses 'Starbug' fibre positioning robots. MANIFEST, when coupled to the telescope's planned seeing-limited instruments, offers access to larger fields of view; higher multiplex gains; versatile reformatting of the focal plane via IFUs; image-slicers; and in some cases higher spatial and spectral resolution. The Prototyping Design Study phase for MANIFEST, nearing completion, has focussed on developing a working prototype of a Starbugs system called TAIPAN, for the UK Schmidt Telescope (UKST), which will conduct a stellar and galaxy survey of the Southern sky.

TAIPAN is a spectroscopic instrument designed for the UK Schmidt Telescope at the Australian Astronomical Observatory. The design for TAIPAN incorporates 150 optical fibres (with an upgrade path to 300) situated within independently-controlled robotic positioners known as Starbugs, allowing precise parallel positioning of every fibre, thus significantly reducing instrument configuration time and increasing the amount of observing time.

In addition to the positioning system prototype for MANIFEST, the TAIPAN project includes a new spectrograph and an upgrade to the UKST systems. The spectrograph is an all-refractive 2-arm design that delivers a spectral resolution of R>2000 over the wavelength range 370-870 nm. The UKST upgrade has included replacement of all telescope drive motors and encoders, new telescope hardware and software control systems, and an upgrade to the dome drive and shutter control systems.

In addition to the development of TAIPAN, the MANIFEST Prototyping Design Study has included continued development of the instrument concept to ensure that MANIFEST is optimal and consistent with GMT instrument and telescope designs and interfaces. We have also continued research and development work on key instrument subsystems (Starbugs and the glass field plate) to increase instrument throughput and operating efficiency, reduce costs, and reduce technical risks.

9908-359, Session PS6

WEBSIM-COMPASS: a new generation scientific instrument simulator for the E-ELT

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We present a new generation scientific instrument simulator dedicated to the E-ELT named WEBSIM-COMPASS, and developed in the frame of the COMPASS project. This simulator builds on the WEBSIM simulators developed during the ESO E-ELT Design Reference Mission and Instrument Phase A studies. The WEBSIM-COMPASS observations simulator consists in a web interface coupled to an IDL code, which allows the user to perform end-to-end simulations of all E-ELT optical/NIR imagers and spectrographs foreseen for the future 39m European Extremely Large Telescope, i.e., MICADO, HARMONI, and MOSAIC. The final products of the simulation pipeline correspond to the result of a data reduction softwares with perfectly extracted/reduced data without any systematic error. We give a functional description of this new simulator, emphasizing the new functionalities and current developments, and present science cases simulated.

9908-360, Session PS6

Preliminary optical design for the Common Fore Optics of METIS

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METIS is the Mid-infrared E-ELT Imager and Spectrograph, which will provide outstanding observing capabilities, focusing on high angular and spectral resolution on the largest telescope on Earth. It consists of two diffraction-limited imagers, providing also low and medium resolution long slit spectroscopy, operating in the LM and NQ bands respectively and an IFU fed diffraction-limited high-resolution (R=100,000) LM band spectrograph. These science subsystems are preceded by the Common Fore Optics (CFO), which re-images the focal plane of the EELT inside METIS and provides the following essential functionalities: calibration, chopping, image de-rotation, thermal background and stray light reduction. The CFO will be the core optical system of the instrument and it will provide the interface towards the imagers, the spectrograph, the single conjugate adaptive optics system and the warm calibration unit. METIS will also provide coronagraphy for all operating modes to achieve high contrast imaging and the intermediate focal plane and pupil plane of the CFO will be populated by the components of apodizing phase plate and vortex coronagraphs.

In the current paper we discuss the optical requirements, external and internal interfaces of the CFO as a starting point and then present the design steps that were taken to fulfil those requirements. Different all-spherical optical architectures, based on Offner relays and modified Schwarzschild systems are presented and compared. A new type of all-spherical three mirror optical relay is presented based on the Offner system that has an accessible pupil and exceptional optical performance that fit the purpose of the CFO perfectly. After identifying the key components, we present the numerical scoring method that we use to determine the order of components that best fulfils the relevant scientific and technical requirements. We detail the manufacturing strategy of the optical components, discuss the alignment plan and elaborate on CFO folding and packaging that are always essential parts of the opto-mechanical design process, especially for cryogenic instruments. We show the evolution of the CFO optical design from the conceptual design, which was based on a single relay to the preliminary optical design containing two subsequent relays. We describe the optical performance of the baseline design and outline the necessary trade-offs regarding field of view, chop-throw, sampling, spectral coverage and optical system complexity. We present the wavefront error budget for the CFO, the corresponding tolerance analyses on manufacturing and alignment and we also show the results of the finite element analyses that address the heat- and gravity-induced surface form deformation of optical components.

9908-362, Session PS6

Can the European ELT detect super-Earths? Measuring the contrast limit of an image slicer spectrograph in a laboratory experiment

Matthias Tecza, Niranjan A. Thatte, Univ. of Oxford (United Kingdom)

The European Extremely Large Telescope (E-ELT) is a 39-m telescope currently being constructed in Northern Chile. It will revolutionary step in capabilities for ground-based astronomy when it goes on sky in around 2024. One of the highest scientific priorities for the E-ELT is to characterise exo-planets and to take images of Earth-like planets. A dedicated planetary camera and spectrograph (ELT-PCS, also called EPICS) is part of the planned suite of ELT instruments and will provide a complete toolkit to characterise planetary systems. Detailed design and construction (Phase B) of ELT-PCS will start as soon as the R&D for specific components reaches

the required technology readiness level.

In this paper we discuss part of the ELT-PCS R&D work comparing different integral-filed-spectrograph (IFS) concepts, in particular our work on image-slicer based spectrographs. This builds on the IFS work package of the EPICS Phase A study investigating both lenslet-array and image-slicer based IFSs, where we demonstrated that an image-slicer based IFS can provide the required contrast. In the current ELT-PCS R&D phase we will confirm these very promising results with a laboratory experiment to quantify the limitations on the contrast ratio that can be achieved with an image-slicer based IFS. The Oxford test-bed will use components from the Phase A experimental setup with the exception of the image slicer (that was borrowed from another instrument that is now on-sky) and a new, low resolution prism disperser. The image slicer and new prism disperser will be designed and manufactured for high-contrast and a large number of spaxels to match the specifications of the lenslet-array. Over a two year period we setup, aligne and test the bench spectrographs including the new disperser and image slicer. Finally we integrate our image-slicer based IFS with the ESO test bench, conduct contrast measurements, and analyse our results.

9908-363, Session PS6

Developing an integrated concept for the E-ELT Multi-Object Spectrograph (MOSAIC): design issues and trade-offs

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We present a discussion of the design issues and trade-offs that have been considered in putting together a new concept for MOSAIC, the multi-object spectrograph for the E-ELT. MOSAIC aims to address the combined science cases for E-ELT MOS that arose from the earlier studies of the multi-object and multi-adaptive optics instruments, OPTIMOS-EVE and EAGLE. The resulting concept provides an integrated focal plane that can deliver either GLAO-fed multi-object spectroscopy of single targets with high multiplex, or a more modest multiplex for MOAO-fed integral field spectroscopy of extended targets at medium-high spatial resolution in the red/NIR.

9908-364, Session PS6

Preliminary design study of the integral field unit for the E-ELT Harmoni instrument

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HARMONI is a visible and near-infrared (0.47 to 2.45 μm) integral field spectrograph, providing the E-ELT's core spectroscopic capability, over a range of resolving powers from R~500 to R~20000.

We present in this paper, the different concepts for the design of the HARMONI Integral Field Unit for the visible and IR science. This subsystem makes the link between HARMONI Preoptic and the 4 Spectrographs. It is composed of a field splitter/ relay system and an image slicer that creates from a rectangular Field of View a very long (532mm) pseudo-slit at the entrance of each spectrograph. We present 2 solutions based on a parabolic image slicer and one based on a cylindrical image slicer. From one concept to the other, we seek to reduce cost and improve ease of manufacture and alignment.

HARMONI is also considering a single visible spectrograph for the full field of view and we present a possible image slicer for this option.

9908-365, Session PS6

Development of cryogenic components based on COTS parts for the HARMONI instrument

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HARMONI is an integral field spectrograph working at visible and near-infrared wavelengths over a range of spatial scales from ground layer corrected to fully diffraction-limited. The instrument has been chosen to be part of the first-light complement at the European Extremely Large Telescope (E-ELT). The large size of the HARMONI instrument and its cryogenic operation is a challenge from the point of view of the mechanics and electronics design. The IAC is in charge of the development of the 'Instrument Pre-Optics' and the 'Instrument Control Electronics'. As a part of these work packages, the design and prototyping of two important components is ongoing. One of the main goals of these developments is the use of COTS (Commercial-Off-The-Shelf) parts as much as possible, since their use will benefit the project reducing costs and shortening the schedule. Nevertheless, the applications of these standard commercial parts in cryo-vacuum environments is often very difficult and represents a technological challenge.

The first development is a 'Cryogenic Pupil Mask Rotator' in charge of shielding the image of the secondary mirror spider in the pupil of the instrument. Since the position of the spider image in the instrument's pupil depends on the telescope position, the mask rotator must track very accurately the telescope motion. Its design is based on a hollow shaft brushless motor and a high resolution capacitive encoder, both being standard industrial grade parts. One first prototype of a direct drive motor has been built and tested. The necessary extremely slow rotary motion (typ. 15 arcsec /s) is a challenge for controlling the direct drive motor since doesn't exists any mechanical reduction. The design of the direct drive motor and the obtained results so far are presented.

The second development is a 'Cryogenic Fast Shutter' in charge of set the instrument detectors exposure time. The position and speed shape of the shutter motion must be accurate and synchronized with the detector controller electronics. Our design is based on a voice coil and a commercial encoder as motion feedback. Several feedback sensor technologies have been considered. The main difficulty is to find a feedback sensor able to work in cryo-vacuum environment and fast enough to close the position control loop of the shutter. A promising technology based on conductive plastic is currently being tested and the present paper describes the results obtained up to now.

9908-366, Session PS6

Novel instrument concepts for characterizing directly-imaged exoplanets

Christoph U. Keller, Leiden Observatory (Netherlands)

Current high-contrast imagers are optimized to find new exoplanets; they minimize diffracted starlight in a large area around a star. I will present novel instrumental approaches that are optimized to characterize these discoveries by minimizing starlight in a small area around the known location of an exoplanet. By trading higher performance for a smaller dark area, it is possible to obtain spectra of known exoplanets with up to 100 times better contrast and 1000 times higher spectral resolution than planet-finding imagers.

I will discuss 5 innovative technologies that minimize the starlight at the location of an exoplanet to achieve breakthrough performance improvements: 1) coronagraphs that remove virtually all starlight over an octave in wavelength while transmitting more than 90% of the exoplanet signal; 2) holographic wavefront sensors that measure aberrations in the science focal plane; 3) ultra-fast adaptive optics systems that minimizes these aberrations; 4) direct minimization of the remaining starlight; and 5) observing and data reduction strategies that use stored focal-plane-sensor and adaptive-optics information to optimally extract the exoplanet spectrum.

By integrating these technologies with a high-resolution, integral-field spectrograph that can resolve the Doppler shift and the polarization difference between the starlight and the reflected light from the exoplanet, it will be possible to determine the atmospheric composition, temperature and velocity structures of cool and warm giant gas exoplanet and their spin rotation rate and orbital velocity. This will ultimately allow the upcoming 25-40-m telescopes to characterize rocky exoplanets in the habitable zone to look for signatures of life.

9908-367, Session PS6

Challenges and proposal of a MUSE-like instrument for the E-ELT

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The extraordinary technical and scientific success of MUSE since its installation on the VLT raises inevitably the question of the next step in terms of Wide Field Integral Field Spectrograph Instrumentation.

The natural trend is to follow the telescope evolution with the start of the different ELT projects and their dramatic increase of primary mirror diameter. However this evolution opens new questions and new challenges.

The first one is of course related to the larger primary mirror and as consequence, the increased plate scale of instrument focal plane. If ultimately this increase is greatly beneficial in terms of sensitivity and diffraction limit, it also strongly limits at the end the size of one instrument Field of View.

The second natural tendency, as one can observe on the different ELTs instruments is to go to the infrared wavelength region and reach for the higher redshifts. But in the context of a Wide Field Integral Field Spectrograph this becomes, because of the IR detector cost, economically and industrially particularly challenging, if not impossible at all.

Then on the other side, the visible and moreover, the bluer part of the spectra coupled with a Wide Field of View presents a real challenge for the Adaptive Optics system.

After discussing the possible science case of such an instrument, this paper will present the different technical options to face these challenges, discuss their performances and feasibility. The choice to move towards the infrared and/or the blue end of the spectra will then be discussed and evaluated in terms of science, feasibility and general interest in the ELT instrumental scene.

Finally an instrument concept will be proposed for the E-ELT. This concept will hold the feasibility and possible performances of such instrument and show a path towards a new generation of Wide Field Integral Field Spectrograph for the ELTs.

9908-368, Session PS6

Serendipitous surveys on extremely large telescopes: their scientific goals and constraints on instrument design

Matthew Horrobin, Univ. zu Köln (Germany)

The upcoming generation of Extremely Large Telescopes represent an unprecedented leap in the collecting power of optical telescopes. As the majority of proposed science instruments only use a small part of the focal plane, there is an opportunity to design an off-axis instrument for serendipitous surveys. Such a survey will be capable of sampling millions of faint galaxies and will also be a powerful tool for sampling transient objects, both near and far. This talk discusses the scientific goals of such a survey, and the instrumentation need to make it successful.

By analysing a typical years set of VLT observations we have defined a baseline serendipitous survey, which we use to predict the depth and coverage of ELT observations. We predict the number of faint targets and transient events that will be observed. These results are compared with those expected for the LSST and we highlight the advantages of parallel serendipitous surveys.

9908-369, Session PS6

Simulated observations of high-redshift galaxies with the HARMONI spectrograph for the European Extremely Large Telescope

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We show the results of a study into the performance of the E-ELT integral field spectrograph HARMONI for observations of galaxies at redshift 2-4. Using the instrument simulation pipeline HSIM, we performed mock observations of galaxies extracted from high-resolution cosmological simulations, which provide far richer input data than simple model galaxies and for which we have complete knowledge of their "true" properties. We describe the software tools developed to convert the simulation data into a spectral cube containing the spatial and spectral properties of the galaxy's light. From the mock observations we estimate how well the intrinsic properties of the galaxy, not just its kinematics but also its stellar population characteristics and star formation history, can be recovered using commonly used analysis tools. The HSIM pipeline also allows us to study observational biases and their likely impact on the data. We discuss the implications of the project for the future science with HARMONI in the critical redshift regime for mass assembly in galaxies.

9908-370, Session PS6

Development of the LOTUCE2 prototype for E-ELT's dome-seeing measurements

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LOTUCE2 (LOcal TUrbulenCe Experiment 2) is based upon the simultaneous measurement of the angle-of-arrival fluctuations affecting four or more laser beams in order to characterise the optical turbulence occurring within a telescope enclosure. The first prototype comprised a series of mirrors and beam-splitters that redirected the incoming laser beams into a single CCD detector through a telescope. Tests carried out with a predecessor prototype at La Silla observatory have shown that vibration-induced signal corruptions are not only of the same amplitude as the turbulence-induced signals, but are furthermore cross-correlated throughout the different baselines. LOTUCE2 upgrade's main objectives are the isolation of the instrument from environment-induced vibrations, and even more importantly the minimisation of any residual vibration cross-contamination, which significantly corrupts the angle-of-arrival fluctuation covariances. In Proc. SPIE 91479R, 2014 we presented the main design of LOTUCE2 and the rational behind it, including the choice of detectors and the corresponding off-the-shelf spherical lenses-based optical design according to the desired sensitivity to optical turbulence-induced angle-of-arrival fluctuations. We have also discussed a generic optical turbulence model and how it may manifest in LOTUCE2's data, including the effects of a non-Kolmogorov turbulence and inner scale parameterisation.
The assembly of LOTUCE2 however posed a few technical challenges, especially related to the key aspect of the simultaneousness of measurements. We have to ensure that all measurements taken at each detector correspond to simultaneous (within an acceptable range of error) snapshots of the optical turbulence. The reason for this is that the main analysis of the optical turbulence statistical properties is based upon spatial covariances, and only partially on temporal spectra. Other important aspects to be sure of are that the system is stable, that there are no losses in data, that time sampling (primarily for spectral analysis) is uniform, and that the performance of the system does not degrade over time. A laboratory experiment to ensure these conditions has been conducted, which has led to some modifications of the computational hardware setup and the corresponding software implementation relatively to what were anticipated initially. We submit a presentation where we detail the results from the above-mentioned experiments, the new hardware setup and software implementation of the instrument, as well as the actual opto-mechanical assembly we realised so that the turbulence in an enclosure is probed with non-horizontally propagating beams. Other aspects we present include a different strategy for the plate-scale calibration. In addition to presenting LOTUCE2's assembly layout, we present the results of the preliminary results from optical-turbulence measurements, highlighting the methods we implemented for data reduction and real-time optical turbulence parameters inversion using artificial neural networks. We also discuss the reliability of the measurements, the precision of the results, as well as the robustness of the instrument overall.

9908-371, Session PS6

Preliminary design study of the high-contrast mode of E-ELT/HARMONI

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HARMONI is a near-IR, IFU-based, first-light instrument of the E-ELT. The spectral characterization of young Jupiter like planets is one of its science cases. High-contrast observations of exoplanets and disks with a medium spectral resolution (R=3500) in a 1.4-2.45 microns band would greatly improve our understanding of the formation process of planets, as well as making it possible to measure chemical abundances in the atmosphere of young Jupiter-like planets. In particular, the planets that will have been observed with SPHERE and the other current direct imaging instrument will be natural targets for HARMONI. This is reflected in the choice of the goal of the high-contrast (HC) mode of HARMONI: to obtain a 1e-6 contrast at 200 mas from the star.

Because HARMONI does not use an atmospheric dispersion corrector (ADC), the HC mode cannot increase contrast by using a focal plane mask such as a Lyot mask or a vortex mask. We have thus proposed to use shaped pupil apodizers to create contrast at about 40-60 mas from the star, and up to 300-500 mas from it (the latter distance corresponds to the AO control radius at 1.4-2.4 microns).

Nevertheless, the star must be blocked to prevent the detector from saturating. This could be done in either two ways: (a) by using a vertical bar in an image plane to block the vertically dispersed image of the star, or (b) by forming the image of the star next to the edges of the splitter pyramid prism, instead of at the center of one of its four surfaces. The first option requires the modification of the current optical design to accommodate for an extra image plane, while the second option raises some concern about light diffusion in the instrument.

We present the methodology and the results of the preliminary study of the HC mode of HARMONI. Our main objective is to estimate the contrast limitation of the instrument. Many factors impact this limitation, and a system analysis of the telescope and the instrument must be performed to take them all into account. We start by considering the residual phase and amplitude errors due to the telescope and its highly segmented primary mirror. The absence of an ADC induces a stronger chromatic beam shift than in a dedicated HC imaging instrument such as SPHERE. This limits the correction of the common path aberrations by the SCAO system. Its impact depends on the conjugated heights of the different optical elements in the instrument prior to the coronagraph. Non-common path aberrations have also been modeled, as well as aberrations due to the rotation of a few optical elements as the telescope tracks a given star. Finally the aberrations associated with the IFS (spatial and spectral cross-talks & diffusion) are also simulated. Raw images obtained with the IFS are fed to post-processing routines that take advantage of field rotation and spectral information to perform differential imaging.

9908-372, Session PS6

The optical design of the G-CLEF Spectrograph: the first light instrument for the GMT

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The GMT-Consortium Large Earth Finder (G-CLEF) is a fiber-fed, high-resolution echelle spectrograph for the Giant Magellan Telescope (GMT).

G-CLEF, to be commissioned in 2021, will be the first scientific instrument operated on the GMT. The G-CLEF passband covers a wide wavelength range, from 350-950nm, and implements an asymmetric white pupil design. Large format CCDs and a dichroic, which separates the dispersed beam into two channels, blue (350-540nm) and red (540-950nm), allow G-CLEF to cover its entire wavelength range in a single exposure on a single CCD in each arm.

In the following paper we present the optical design of G-CLEF. We emphasize some of the unique solutions that allow G-CLEF to deliver excellent performance for several operational modes that address different scientific cases.

The G-CLEF spectrograph is located inside a vacuum chamber within a thermal control system and is mounted on a gravity invariant platform. It is fed by a novel fiber-feed that allows observations at several resolutions and modes: two high-resolution pupil-sliced modes (R=108,000), each using seven 100um core fibers, a medium resolution mode (R=40,000) using a 320um core fiber, and a high throughput mode (R=20,000) using a 450um core fiber. G-CLEF operates in a Multi-Object Spectrograph (MOS) mode using the GMT Many Instrument Fiber System (MANIFEST) interface. In order to minimize focal ratio degradation the fibers are fed at f/3 by focal ratio reducers located at the telescope telescope-fiber interface. Custom optics located inside the spectrograph vacuum enclosure convert the fiber output beams to f/8 – the working focal ratio of the spectrograph.

G-CLEF uses volume phase holographic (VPH) grism cross dispersers that offer higher throughput than surface relief gratings. Pick-off mirrors inside the G-CLEF cameras deflect light that is dispersed by the cross dispersers into the zeroth order to feed exposure meters (one per camera) located outside of the instrument vacuum enclosure. Finally, we describe the spectrograph blue and red cameras, comprised of 8 and 7 elements respectively, with one aspheric surface in each camera. Both cameras have a focal length of 450mm and a working f/# of 2.25, resulting in an image scale of 93.75 microns/arcsec. Both cameras utilize a common Mangin mirror, located at an intermediate focus between the spectrograph's two off-axis collimating mirrors, to correct for the cylindrical field curvature inherent in white pupil echelle spectrographs and deliver excellent image quality. Both cameras are independently testable outside of the spectrograph optical train using collimated white light.

9908-373, Session PS6

The Infrared Imaging Spectrograph (IRIS) for TMT: the ADC optical design

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We present the current optical design for the IRIS Atmospheric Dispersion Corrector (ADC). The ADC is designed for residual dispersions less than ~1mas across a given passband at elevations of 25 degrees. Since the last report, the area of the IRIS Imager has increased by a factor of four, and the pupil size has increased from 75 to 90mm, both of which contribute to challenges with the design. Several considerations have led to the current design: residual dispersion, amount of introduced distortion, glass transmission, glass availability, and pupil displacement. In particular, it was found that there are significant distortions that appear (two different components) that can lead to image blur over long exposures. Also, pupil displacement increases the wave front error at the imager focus. We discuss these considerations, discuss the compromises, and present the final design choice and expected performance.

9908-374, Session PS6

The opto-mechanical design of the GMT-Consortium Large Earth Finder (G-CLEF)

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The GMT-Consortium Large Earth Finder (G-CLEF) is a fiber-fed, optical echelle spectrograph that has been selected as the first light instrument for the Giant Magellan Telescope (GMT) which has begun construction at the Las Campanas Observatory in Chile. G-CLEF has been designed to be a general-purpose echelle spectrograph with precision radial velocity (PRV) capability for exoplanet detection. The radial velocity (RV) precision goal of G-CLEF is 10 cm/sec, necessary for detection of Earth-sized exoplanets. This goal imposes challenging stability requirements on the optical mounts and the overall spectrograph support structures especially when considering the instrument's operational environment. The accuracy of G-CLEF's PRV measurements will be influenced by minute changes in temperature and ambient air pressure as well as vibrations and micro gravity-vector variations caused by normal telescope tracking. For these reasons we have chosen to enclose G-CLEF's spectrograph optics in a thermally controlled, vibration isolated vacuum chamber at a gravity invariant location on GMT's azimuth platform. Additional design constraints posed by the GMT telescope include: a limited space envelope, a thermal emission ceiling, and a maximum weight allowance. Other factors, such as manufacturability, serviceability, available technology and cost are also significant design drivers. These considerations must all be managed while ensuring that performance requirements are achieved.

In this paper, we discuss the design of G-CLEF's optical mounts and support structures including the choice of a low-CTE carbon-fiber optical bench to minimize the system's sensitivity to thermal gradients. We discuss design choices made within the vacuum chamber geared towards minimizing the influence of daily ambient pressure variations on image motion during observation. We discuss the design of G-CLEF's insulated enclosure and thermal control systems which maintain the spectrograph at milli-Kelvin level temperature stability while simultaneously limiting the maximum thermal emission into the telescope dome. Also discussed are micro gravity-vector variations caused by normal telescope slewing, their uncorrected influence on image motion, and how they are dealt with in the design. We discuss G-CLEF's front-end assembly and fiber-feed system as well as other interface challenges presented by the telescope, enclosure and neighboring instrumentation.

9908-375, Session PS6

Optomechanical design concept for the Giant Magellan Telescope Multi-object Astronomical and Cosmological Spectrograph (GMACS)

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We describe the conceptual optomechanical design for the Giant Magellan Telescope Multi-object Astronomical and Cosmological Spectrograph (GMACS), a wide-field, multi-object, moderate-resolution optical spectrograph for the Giant Magellan Telescope (GMT). In this paper we describe the details of the GMACS optomechanical design, including the requirements and considerations leading to the design, mechanisms, optical mounts, and predicted flexure performance.

9908-376, Session PS6

Optical design concept for the Giant Magellan Telescope Multi-object Astronomical and Cosmological Spectrograph (GMACS)

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We present a conceptual optical design for GMACS, a wide field, multi-object, optical spectrograph currently being developed for the Giant Magellan Telescope (GMT). We include details of the optical design requirements derived from the instrument scientific and technical objectives and demonstrate how these requirements are met by the current design. Detector specifications, field acquisition/alignment optics, and optical considerations for the active flexure control system are also discussed.

9908-377, Session PS6

Design and analysis of the NFIRAOS thermal optics enclosure

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The Narrow Field InfraRed Adaptive Optics System (NFIRAOS) will be the first-light facility Adaptive Optics system for the Thirty Meter Telescope (TMT). In order to meet the optical performance and stability specifications essential to leveraging the extraordinary capabilities of the TMT, all of the optical components within NFIRAOS will be protected within a large thermally-controlled optics enclosure (ENCL). Among the many functions performed by the ENCL, the most critical functions include providing a highly stable, light-tight, cold, dry environment maintained at 243±0.5 K for the NFIRAOS opto-mechanical sub-systems and supporting TABL structure. Although the performance of the ENCL during the science operation of NFIRAOS is critical, the maximum thermal loading will be defined by the cool-down/warm-up cycle which must be accomplished within a time-frame that will minimize the on-sky operational impact due to daytime maintenance work. This study describes the thermal/mechanical design development and supporting analyses (analytical and finite element analyses (FEA)) completed during the preliminary design phase and through the current progression of the ENCL final design phase.

The walls of the ENCL consist of interlocking, multilayered, thermally insulated panels, which are supported by an externally located structural framework which attaches to the NFIRAOS Instrument Support Structure. The regulation of the interior ENCL wall surface temperature to within ±0.5 K requires that the heat flux into the interior of NFIRAOS be eliminated by cooling a thermal conduction plate embedded between multiple layers of insulation. The thermal design of the enclosure was evaluated for both steady-state (SS) performance and transient performance (cool-down and warm-up cycles). The transient analysis utilizes a hybrid of a one-dimensional thermal network approach combined with three-dimensional conjugate heat transfer analyses of explicit opto-mechanical components within the ENCL. Many design-parameter combinations were evaluated to determine the performance impact of cooling power and transient temperature profiles. The results derived from the analyses of these design iterations indicate the multi-layer enclosure wall design will meet all thermal requirements. During SS operation, the interior temperature variation is within ±0.5 K of the target operational temperature, while the heat influx from the exterior TMT environment is 1528 W (extracted by the embedded cold plate). The transient cool-down cycle will take approximately 15 hours to complete and requires the in-situ air handling units (AHU) to deliver 14KW of cooling power (derated for the TMT site conditions) throughout the interior space of the NFIRAOS ENCL.

9908-378, Session PS6

High-contrast imaging with METIS

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The Mid-infrared E-ELT Imager and Spectrograph (METIS) for the European Extremely Large Telescope (E-ELT) consists of a diffraction-limited imager at L/M and N/Q band with medium resolution spectroscopic capabilities, and an integral field unit for high spectral resolution spectroscopy over the L and M bands. One of the science cases that METIS addresses is the characterization of faint circumstellar material and exoplanet companions through imaging and spectroscopy.

We present our approach for high contrast imaging with METIS, covering diffraction suppression with coronagraphs, the removal of slowly changing optical aberrations with focal plane wavefront sensing, interferometric imaging with non-redundant masks, and observing strategies for both the imagers and IFU image slicers.

9908-379, Session PS6

Generalized atmospheric dispersion correctors for TMT

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The Thirty Meter Telescope (TMT) is unbaffled and has stability requirements tighter than the previous generation of 10-m class telescopes, leading to tougher requirements on atmospheric dispersion correctors (ADC's). Since instruments are internally baffled, ADC's may no longer shift the position of the telescope exit pupil. Designs that control pupil position are explored.

9908-380, Session PS6

The Infrared Imaging Spectrograph (IRIS) for TMT: Prototyping of cryogenic compatible stage for the Imager

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The IRIS Imager requires multi-axis motion control of optical components in order to change observation modes and minimize the wave front error due to motion of the field. The motion control can be provided by an opt-mechanical stage which is operable under vacuum and cryogenic environment. Also the stage for the IRIS Imager is required to survive for 10 years without maintenance. One of the stages is for the cold stop that is located at pupil. First of all, we assumed that a stage for the cold stop carries an 80 mm diameter pupil mask and requires one rotational axis and two translational axes to align and retract the pupil mask. We noticed that it was hard to obtain a 3-dof stage with 80 mm clear aperture from commercial market and then decided to start prototyping.

Mechanical design of the prototype was started based on the requirement for the cold stop stage. However, degree of freedom of the stage was reduced to one rotation and one translation due to constraint of test environment. The prototype was designed as a double-deck stage, upper rotational stage and lower translational stage. The rotary stage is made of stainless steel with consideration of CTE of rotary bearing material, however the other parts are made of Aluminum because of its high thermal conductivity and specific rigidity. The rotary stage base equips stress relief mechanisms to absorb CTE difference between Stainless steel and Aluminum. One of concerns was that heat from the motor will generate temperature gradient and would cause unexpected stress to linear motion guide and failure. To control that, the rotary stage base was designed as not ordinary shape but horseshoe shape. Most of components are selected to take advantage of heritage from existing astronomical instruments. Stepper motors from Phytron, Inc. were chosen because of their proven performance under cryogenics. In contrast, mechanical components with lubricants such as bearings, linear motion guides and ball screws were modified to survive cryogenic environment. Standard balls were replaced with ones made of ceramics or processed with MoST(TM) coating. A drive mechanism including 160 teeth driven gear for rotary stage was fabricated at Mechanical Engineering Shop of Advanced Technology Center, National Astronomical Observatory of Japan. A motion controller and motor drivers from Newport Corporation is employed for the prototype. The performance proving test was carried out to evaluate errors such as wobbling, rotational and translational positioning error. We achieved 0.002 deg rms wobbling, 0.03 deg rms rotational positioning error and 0.017 mm rms translational positioning error. Also durability under anticipated load condition has been conducted.

In this article, we report the detail of mechanical design, fabrication, performance and durability of the prototype.

9908-381, Session PS6

The Infrared Imaging Spectrograph (IRIS) for TMT: multi-tiered wavefront measurements and novel mechanical design

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The InfraRed Imaging Spectrograph (IRIS) will be the first light adaptive optics instrument on the Thirty Meter Telescope (TMT). IRIS is a collaboration between Caltech, the University of California, NAOJ and NRC Herzberg. In this paper, we present novel aspects of the Support Structure, Rotator and On-Instrument Wavefront systems being developed at NRC Herzberg. IRIS is suspended off the bottom port of the Narrow Field Infrared Adaptive Optics System (NFIRAOS) and provides its own image derotation to compensate for sidereal rotation of the focal plane. This arrangement is a challenge because NFIRAOS is designed to host two other science instruments, which imposes strict mass requirements on IRIS. As the mechanical design of all elements has progressed, we have been tasked with keeping the instrument under seven tonnes. This requirement has resulted in a mass reduction of 30 percent for the support structure and rotator compared to the most recent IRIS designs. To accomplish this goal while still being able to withstand earthquakes, we developed a new design with composite materials. As IRIS is a client instrument of NFIRAOS, it benefits from NFIRAOS' superior AO correction. IRIS plays an important role in providing this correction by sensing low-order aberrations with three On-Instrument Wavefront Sensors (OIWFS). The OIWFS consist of three independently positioned natural guide star wavefront sensor probe arms that patrol a 2-arcminute field of view. We expect tip-tilt measurements from faint stars within the IRIS imager focal plane will further stabilize the delivered image quality. We describe how the use of On-Detector Guide Windows (ODGWs) in the IRIS imaging detector can be incorporated into the AO correction. In this paper, we present our strategies for acquiring and tracking sources with this complex AO system, and for mitigating and measuring the various potential sources of image blur and misalignment due to properties of the mechanical structure and interfaces.

9908-382, Session PS6

A concept for seeing-limited IR spectroscopy at GMT

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The initial instrument suite for the Giant Magellan Telescope includes seeing-limited multi-object and precision radial velocity spectrometers, but no capability for infrared spectroscopy. Several high level science objectives of the observatory (e.g. Epoch of Reionization studies) can only be realized in the IR, and this need will eventually be addressed by instruments optimized for use with GMT's adaptive optics system. In this contribution we explore designs for an affordable seeing-limited near-IR spectrometer that could be developed on a short time scale, enabling early science for a range of topics highlighted in the GMT Science Book.

We have considered multiple design options; the principal model presented here draws heritage from the Magellan FIRE instrument, with a number of important differences. It is a cross-dispersed R2 echelle, based around a white pupil layout with a small degree of asymmetry. This design delivers continuous wavelength coverage from 0.88-2.50 microns at R=6000 for a single 0.7" x 8.0" entrance slit.

It uses a monolithic echelle grating over 42 orders, with dichroics splitting the dispersed beam into J, H, and K arms prior to cross dispersion. By isolating these arms, we may use VPH gratings for cross dispersion to maximize efficiency, and the spectral format maps well onto H2RG focal plane arrays. The echelle grating may be swapped with a flat mirror to access an alternate operating mode, with simultaneous JHK longslit coverage at R~1000.

Fast camera optics are required to best leverage the GMT's collecting area, since detector read noise limits the performance of FIRE and similar instruments on 6-10 meter telescopes. Accordingly, near-IR spectroscopy is a regime where giant telescopes offer favorable performance scaling, even in the seeing limit. Near 1 micron such instruments also complement JWST because their inter-line background remains low and JWST/NIRSPEC

is read-noise limited. Our optical design uses cameras with F/1.0 - F/1.25, with polychromatic entrance pupil diameter of 120mm.

Every effort has been made to reduce cost and mechanical complexity, with budget constraints in mind. All detectors and gratings are available as catalog items, and the optical layout fits within a vessel 1 meter in diameter and 2 meters long, simplifying design of the vacuum cryogenic system. There are only two user-controlled cryogenic mechanisms, one to select slits, and another to switch to low dispersion mode. We discuss concepts for additional servo mechanisms to condition instrument pointing/flexure and control the pupil stop.

This relatively small instrument can easily be accommodated in the volume envelope of GMT's Gregorian instrument platform. By using a dichroic to fold the telescope beam, it may be used in conjunction with the direct Gregorian optical spectrometer to achieve complete and simultaneous coverage of the full optical and near-IR bands. This conceptual design study demonstrates the potential for development of relatively affordable instruments at the ELT scale, in response to the pressures of joint funding for these telescopes and their associated instrument suites.

9908-383, Session PS6

Optical design of the post-focal relay of MAORY

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The Multi Conjugate Adaptive Optics Relay (MAORY) for the European Extremely Large Telescope is planned to be located on the straight-through port of the telescope Nasmyth platform and shall re-image the telescope focal plane to a wide field camera (MICADO) and a possible future second instrument. By means of natural and artificial (laser) reference sources for wavefront sensing, and of deformable mirrors for wavefront correction, MAORY shall be able to compensate the wavefront disturbances affecting the scientific observations, achieving high Strehl ratio and high sky coverage.

A trade-off study among different design options has been carried out addressing optical performance at the exit ports (wave front error, field distortion, throughput), structure stability, interface constraints (mass, size, location and accessibility of the two client instruments), adaptive optics performance and budget.

We show the consolidated baseline configuration of the opto-mechanical design as a result of Phase B1.

9908-384, Session PS6

Wavelength dependence of star images formed by large ground-based telescopes including ELTs

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The angular size and shape of star images delivered by large ground-based telescopes – with or without Adaptive Optics (AO) – can vary greatly over the optical wavelength region, 0.3 ?m – 1000 ?m. A particularly diverse range of appearances is anticipated for future images delivered by the eagerly-anticipated 40-meter diameter European-Extremely Large Telescope (E-ELT). In this talk, we examine star image properties as a function of wavelength and use a simple, expedient formulation to generate representative images. Because of its origins in a rigorous formulation that relies only on Maxwell's equations, the formulation does not require 'a priori' assumptions about atmospheric turbulence properties, Kolmogorov or other. These turbulence properties, together with relevant properties of the telescope and AO system, combine to determine the average star image intensity envelopes. As indicated in the talk, all of these properties can be established (on-site and as-needed) from readily-measurable properties of the most general kind of star image – the core and halo image. As wavelengths range from near-UV towards long-wavelength IR, sooner or later all star images ultimately morph through the same three basic forms: halo-only, core-and-halo, and core-only. Given any large reflector telescope, by simply imaging a star at a wavelength consistent with a core-and-halo image and then measuring certain basic properties of that image, we can immediately predict from these properties how the star will look at any other wavelength.

A core-and-halo star image obtained at 1.65 ?m by the AO-equipped Keck II instrument is used to illustrate both the image-characterization and image-generation procedures. Images created in this way show how stars might have looked with the Keck II instrument in the same seeing conditions at various other visible and IR wavelengths. Other images show how stars will likely appear in the 40-meter E-ELT instrument, with present-day AO performance levels assumed, and also marginally improved levels in anticipation of future AO advances.

The effects on star images of scintillation and residual uncorrected phase are examined in detail. Both mechanisms cause light energy to be scattered from the centers of star images, degrading Strehl intensity and creating background haze that can conceal faint nearby objects. While an efficiently-functioning AO-equipped telescope should, in theory, be able to deliver substantially diffraction-limited images at all optical wavelengths, because of the practical limitations of present-day AO technology, usually only partial correction is possible at shorter wavelengths, visible wavelengths in particular. In the case of the E-ELT telescope, unless significant advances have been made in AO technology by the time of first light, the irradiance in the center of star images delivered by this instrument at the shortest visible wavelength, 0.4 ?m, is reasoned to be about 10-magnitudes less than the theoretical maximum value. Consequently, star images delivered by the E-ELT instrument at visible wavelengths may be no better than those delivered by a diffraction-limited, space-based 1-meter instrument. However, for wavelengths longer than about 1.5 ?m, scattering issues rapidly subside and it then becomes increasingly likely that the formidable diffraction-limited resolution potential of this magnificent instrument will be fully realized.

9908-385, Session PS6

Flowdown of the TMT astrometry error budget(s) to the design of the first-light instrument IRIS

Matthias Schöck, Thirty Meter Telescope (United States); David R. Andersen, NRC - Herzberg Astronomy & Astrophysics (Canada); John Rogers, Thirty Meter Telescope (United States)

TMT has defined the accuracy to be achieved for both absolute and differential astrometry in its top-level requirements documents. Because of the complexities of different types of astrometric observations, these requirements cannot be used to specify system design parameters directly. The TMT astrometry working group therefore developed detailed astrometry error budgets for a variety of science cases. These error budgets detail how astrometric errors propagate through the calibration,

observing and data reduction processes, and need to be condensed into sets of specific requirements that can be used by each subsystem team for design purposes. We show how this flowdown from error budgets to design requirements is achieved for the case of TMT's first-light Infrared Imaging Spectrometer (IRIS) instrument. We describe the process in general, provide examples of how it is executed and list the most significant consequences for the IRIS design.

9908-386, Session PS6

The Infrared Imaging Spectrograph (IRIS) for TMT: optical design of IRIS imager with "co-axis double TMA"

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IRIS (InfraRed Imaging Spectrograph) is one of the first generation instruments for Thirty Meter Telescope (TMT). IRIS is composed of a combination of near-infrared (0.84-2.4um) diffraction limited imager and integral field spectrograph. To achieve diffraction limited resolutions at wavelengths longer than 1 um, IRIS can utilizes the advanced adaptive optics system NFIRAOS (Narrow Field Infrared Adaptive Optics System) and has integrated on-instrument wavefront sensors (OIWFS). However, IRIS itself has challenging specifications. Firstly, wavefront error of overall system should be less than 40 nm in Y, z, J, and H-band and 42 nm in K-band over a 34.0x34.0 arcsecond field of view. Secondly, throughput of the imager components should be more than 42%. To achieve the extremely low wavefront error and high throughput, all reflective design has been newly proposed. We have adopted a new design policy called "Co-Axis double-TMA", which cancels the asymmetric aberrations generated by "Collimator TMA" and "Camera TMA" efficiently. The latest imager design meets all specifications, especially, wavefront error is less than 17.3 nm and throughput is more than 50.8 %. However, to meet the specification of wavefront error and high throughput as built performance, IRIS imager requires the mirrors with low surface irregularity and high throughput coating in cryogenic and high-level AIV. To deal with these problems, we have done the tolerance analysis and found that total pass rate is almost 99% in the case of gauss distribution and more than 90% in the case of parabolic distribution using four compensators. We also have done AIV plan and feasibility check of the optical elements. In this paper, we will present the detail of this optical system.

9909-1, Session 1

MagAO: status and science

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The AO system at the Magellan Clay telescope at Las Campanas Observatory, Chile, "MagAO," has a 585-actuator adaptive secondary mirror and 1000-Hz pyramid wavefront sensor, operating on natural guide stars from R-magnitudes of -1 to 16. MagAO has been in operation for ~150 regular science nights in the 3 years post-commissioning. MagAO's unique capabilities are simultaneous imaging in the visible and infrared with VisAO and Clio, high performance at an excellent site, and a lean operations model. A wide range of science is pursued with the instrument, from Solar System studies to extrasolar planets, circumstellar disks, and galactic science, with (thus far) ~60 users producing ~20 refereed publications. Some of MagAO's science results include the first ground-based CCD image of an exoplanet, discovery of the first accreting protoplanets, discovery of a new wide-orbit exoplanet, and the first empirical bolometric luminosity of an exoplanet. We will describe the system, operations, calibrations, and science results of this unique facility-class AO instrument.

9909-2, Session 1

imaka: ground-layer AO at Maunakea

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We present the integration and commissioning status for the ground-layer adaptive optics (GLAO) system `imaka on the University of Hawaii 2.2-meter telescope on Maunakea, Hawaii. This GLAO system exploits Maunakea's highly confined ground layer and weak free-atmosphere to push the corrected field of view to ~1/3 of a degree. By using natural guide stars spread over this wide field, we will demonstrate the efficacy of AO with an areal field approaching an order of magnitude larger than any existing or planned GLAO system.

In this presentation we present the unique aspects of the system implementations, how the science cases impact the system, as well as the lessons learned to date designing/fabricating the instrument. The large field of view and the astrometric science case drive the instrument to large optics with strict stability requirements. These bring strong design constraints. In particular, the size, mass, and stability requirements led us to a stiff, lightweight, athermal structure made from carbon-fiber panels. The choice of carbon fiber, however, has other design/use impacts on its use in astronomical instruments. For example, (1) the carbon-fiber panels are hygroscopic so long term changes in their moisture content affect the optical alignment of the system. Since these changes occur over long periods (weeks to months) we believe their effects can be mitigated with care in storage, use, and regular long-term monitoring/calibrations. (2) Given the size of the instrument and the assembly techniques, the carbon-fiber structure on its own has positional accuracies nearly an order of magnitude worse than commonly obtain with aluminum structures (e.g. machine tolerances). We are able to compensate for this initial reduced precision with some forethought on the design of the instrument. In particular, to position elements in the structure we designed in the means to establish, after the structure fabrication, a positional accuracy for each of the critical elements. This combined with an optical design tolerant to misalignment allows us to meet our image quality error budget.

The path-finder nature of `imaka combined with access to a telescope on Maunakea provides a powerful platform for testing a variety of approaches for wide-field AO at a premier astronomical site. `imaka is flexible - at the instrument's front focus different calibration units can slot into a "calibration drawer" to test basic functionality of the GLAO system, provide "pre AO" wavefront sensor telemetry, or calibrate optical distortions. At the rear focus we effectively have an optical table capable of holding a variety of science or "scoring" cameras/wavefront sensors. In addition, `imaka's operational model provides flexibility - we can access useful periods of time on the telescope for each experiment with the instrument configured for a specific set of observations. We summarize the experiments we will be conducting with the system over next year. These include tackling the astrometric precision and accuracy of GLAO with the system in embedded star formation regions with the distortion calibration unit and a wide-field near infrared science camera based on a Teledyne H4RG-15 detector.

9909-3, Session 1

Engineering aspects of the Large Binocular Telescope Observatory adaptive optics systems

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The Large Binocular Telescope (LBT) is equipped with two advanced adaptive optics systems named first light adaptive optics (FLAO), these systems comprise two new and challenging technologies, namely: adaptive secondary mirrors (ASM) and pyramid wavefront sensors (PWS) both requiring significant engineering support.

To maintain two functional and operational AO systems several engineering aspects of both ASMs and PWSs need to be considered, in particular in this paper we address: system safety and reliability, maintenance and repairs, AO calibrations and improvements to the initial design.

The ASMs are subject to several significant risks, the highest being related to human intervention during handling of the units themselves or direct handling of the fragile thin shells. In order to limit these risks we have developed very strict procedures and an inspection regimen to be used during: removal, installation and coating. Other risks are related to wind effect on the thin shells and cooling system. To protect against the first of these risks a safety scheme was implemented in the design phase and has been improved during the operation phase. To protect against the second risk we have had to redesign the cooling system, introducing a more effective coolant leak detection system and temperature control.

In terms of reliability one of the main areas of activity is related to actuator malfunction or loss of calibration. This occurs intermittently causing loss of observing time. We present a plan to implement an automatic scheme for actuator monitoring with a disabling/enabling mechanism in order to prevent time loss due to manual intervention.

We will also discuss optical calibration of the ASMs at the telescope using a dynamic interferometer operating at the long conjugate focus of the ASMs.

For the PWSs the main effort is directed towards keeping the various electro-mechanical components in good conditions as well as developing

reliable and effective procedures for the units' alignment.

While the work towards improving the original design of the ASMs and PWSs is demanding and challenging we demonstrate that the rewards, in terms of reduced downtime and increased performance are significant. This leads us towards our goal of having manageable systems that can operate routinely and with limited oversight.

9909-4, Session 1

ALES: a 1.5-5 micron adaptive optics integral field spectrograph for the LBT

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Integral field spectrographs are an important technology for exoplanet imaging, due to their ability to take spectra in a high-contrast environment, and improve planet detection sensitivity through spectral differential imaging. ALES is the first integral field spectrograph capable of imaging exoplanets from 3-5 μm, and will extend our ability to characterize self-luminous exoplanets into a wavelength range where they peak in brightness. ALES is installed inside LBTI/LMIRcam on the Large Binocular Telescope, and saw first light in June 2015. In 2016A, we are beginning science observations with ALES, which will include spectroscopy of directly-imaged exoplanets, debris and transition disks, comets, and Jovian moons. Additionally, we are planning upgrades that will (1) increase ALES's field-of-view, spectral resolution and wavelength range, (2) decrease inter-spaxel crosstalk at the edges of the ALES field, and (3) implement an interferometric plate-scale that will take IFS images at the diffraction limit of the full 23-meter baseline LBT.

9909-5, Session 2

The infrared imaging spectrograph (IRIS) for TMT: latest science cases and simulations *(Invited Paper)*

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The Thirty Meter Telescope (TMT) first light instrument, IRIS (Infrared Imaging Spectrograph), will complete the preliminary design phase in 2016. The IRIS instrument design includes a near-infrared (0.85 - 2.4 micron) integral field spectrograph (IFS) and wide field imager (32.8"x32.8") that is able to conduct simultaneous diffraction-limited observations behind the advanced adaptive optics system NFIRAOS. The IRIS science case has continued to be developed and new science studies have been investigated to aid in technical performance and design. The IRIS science team has paid particular attention in the selection of filters, gratings, and sensitivities of the entire system. We will present science cases that directly benefit from the parallel mode between IFS and imager, as well as uniqueness of the combination of IFS high spatial resolution observations with moderate (R= 4000 - 8000) resolving power. We discuss the overarching science case for IRIS, and we will present latest results from the end-to-end data simulator for IFS and imager on a variety of science cases, ranging from solar system objects, extrasolar planets, active galactic nuclei, to nearby and distant galaxies. Each of these science cases will be put in context with other upcoming facilities and the importance of complementary high spatial resolution observations. Lastly, we will briefly discuss the necessity of an advanced data management system and data reduction pipeline as further outlined in Walth et al., this conference.

9909-6, Session 2

Photometry in MCAO *(Invited Paper)*

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We will make an overview of the current status of photometric analyses performed with Multi Conjugate Adaptive Optics (MCAO) mounted on 10-m class of telescopes that operated, or are operating, on sky.

Particular attention will be payed to resolved stellar population studies. In fact stars in crowded stellar systems, such as globular clusters or distant galaxies, are ideal test--particles in order to test AO performance. We will present recent results obtained in our observational campaign (PI A. Mc Connachie) using the MCAO system mounted at the Gemini-South telescope, i.e. GeMS. Six globular clusters have been observed in J and K bands. As expected, thanks to the AO system, the K-band limiting magnitude approaches Ks~ 22 mag. The accuracy reached for most of the globular clusters allowed us to reconstruct their Colour Magnitude diagram down to their main sequence knees. The detection and characterization of this feature has permitted to constrain with unprecedented accuracy the absolute ages of some of these clusters (e.g. NGC1851, NGC2808 and NGC5904). For the remaining clusters (e.g. NGC6681, NGC6723 and NGC6652) near Infrared calibration data are needed and have been required. This is a crucial point when exploiting very deep near IR AO imaging.

We will focus on the sensitivity and on the photometric precision reached nowadays. In order to quantify our ability in performing PSF photometry on MCAO images with existing photometric packages, we will use different software (DAOPHOT, Starfinder, Romaphot) on images taken with laser (and eventually natural) guide stars systems, e.g. GeMS@Gemini-South.

Finally, we discuss the kind of science we plan to do and the errors expected when coming (e.g. Linc Nirvana) or future (e.g. MAORY) facilities will be operational on 10-m class or giant ground based telescopes.

9909-7, Session 2

Photometric techniques, performance, and PSF characterization of GeMS, the MCAO system on Gemini South

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GeMS is the first facility class multi-conjugate adaptive optics (MCAO) instrument on the 8-m Gemini South telescope in Chile, and the first to use laser guide stars. We have observed six Galactic globular clusters in J (1.25 ?m) and Ks (2.15 ?m) band for which we have also HST/ACS observations in the visible. We use NGC 1851 as a benchmark with which to judge the science performance of GeMS for photometry, and to develop procedures to best extract the best science performance of the system. We develop techniques to best characterize the empirical PSF, and determine with high accuracy the PSF model for the PSF fitting photometry. We show that the PSF model has to have a large degree of spatial and temporal variability. We use the bright stars in our target also to measure the performance of the MCAO correction in terms of Strehl ratio, FWHM and ellipticity of the PSF. The performance maps provide an additional proof for the need of a varying PSF, and demonstrate that scientific images produced by MCAO require a more careful photometric reduction than seeing-limited observations. Understanding the correct PSF fitting techniques will prove useful for observing with the next generation of Extremely Large Telescopes like TMT and E-ELT, where MCAO will be a central technology.

9909-8, Session 3

Adaptive optics program update at TMT

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The TMT first light AO facility consists of the Narrow Field Infra-Red AO System (NFIRAOS), the associated Laser Guide Star Facility (LGSF) and the AO Executive Software (AOESW). Design, fabrication and prototyping activities of the TMT first light AO systems and their components are now ramping up in Canada, China and in the US. NFIRAOS is an order 60 x 60 laser guide star (LGS) multi-conjugate AO (MCAO) system, which provides uniform, diffraction-limited performance in the J, H, and K bands over 15-30 arc sec diameter fields with 50 per cent sky coverage at the galactic pole, as required to support the TMT science cases. NFIRAOS includes two deformable mirrors, six laser guide star wavefront sensors, one high order Pyramid WFS for natural guide star AO, up to three low-order, IR, natural guide star on-instrument wavefront sensors (OIWFS) within each client instrument, and up to four guide windows on the science detectors (ODGW). The first light LGSF system includes six sodium lasers to generate the NFIRAOS laser guide stars.

In this paper, we will provide an update on the progress in designing, prototyping, fabricating and modeling the TMT first light AO systems and their AO components over the last two years. This will include final design and prototyping/benchmarking activities for NFIRAOS and the NFIRAOS Real Time Controller (RTC), preliminary design and prototyping activities for the LGSF and AOESW, design and prototyping for the deformable mirrors and the visible WFS camera, fabrication and tests for the visible WFS detectors, and further development and tests of candidate lasers. TMT is continuing with detailed AO modeling to support the design and development of the first light AO systems and components. Major modeling topics studied during the last two years include further studies in the area of pyramid wavefront sensing, high precision astrometry, PSF reconstruction for LGS MCAO, LGSF wavefront error budget and sophisticated low order mode temporal filtering.

9909-9, Session 3

The HARMONI laser tomography module

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HARMONI is a visible and near-infrared integral field spectrograph, providing the E-ELT's core spectroscopic capability. It will exploit the E-ELT's scientific niche in its early years, starting at first light. To get the full sensitivity and spatial resolution gain, HARMONI will work at diffraction limited scales. This will be possible thanks to two adaptive optics systems, complementary to each other. Both systems will make use of the telescope's adaptive M4 and M5 mirrors. The first one is a simple but efficient Single Conjugate AO system (good performance, low sky coverage), fully integrated in HARMONI itself. The second one is a Laser Tomographic AO system (medium performance, very good sky coverage). In this paper, we focus on the Laser Tomography AO module.

We present the system choices that has been made, in particular regarding the LGS constellation and the complementary measurement done with the NGS.

In particular, we detail the WFS concept choice that are envisioned for the LGS, and present a first trade-off in terms of performance, of different potential designs. This is particularly relevant for HARMONI, as the baseline will be to work with sub-optimal detectors in terms of total number of pixels. Hence, trade-offs are made between LGS spot sampling, truncation and optical spot shrinking. Still regarding the LGSWFS path, we explore the impact of static aberrations, and differential quasi-static aberrations between the different LGS paths. Finally, we present a first trade-off study between different tomographic approaches.

Regarding the NGS path, we describe the NGSWFS design choice, and the expected performance for a focal plane solution in order to measure Tip-Tilt and Focus. We discuss the definition and required performance for a truth WFS. Finally, we present the estimated performance and resulting sky-coverage based on a full E2E simulation model. Telescope effects such as spyders, phasing, scalloping and wind-shake are introduced in the model.

Finally, we present a list of the required calibrations, and the need for telescope calibration sources vs. on-sky calibration.

9909-10, Session 3

MICADO SCAO specifications, prototyping, concepts and current preliminary design

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MICADO is the E-ELT first light imager, working at the diffraction limit in the near infrared. Optimized to work with the MAORY multi-conjugate adaptive optics module, MICADO will also come with a single conjugate adaptive optics (SCAO) capability motivated by scientific programs for which SCAO will deliver the best AO performance (e.g. exoplanets, solar system science, bright AGNs, etc).

This SCAO capability will be developed within MICADO through a dedicated SCAO module with its natural guide star (NGS) wavefront sensor (WFS), allowing MICADO to work in SCAO stand alone mode without MAORY, and inside MAORY with the same dedicated NGS WFS.

The project has just entered in phase B in October 2015. We are then currently in a phase of prototyping, simulations and preliminary design.

The MICADO SCAO prototyping activities are concerning first the WFS, aiming at guiding the choice of the wavefront sensor, either Shack-Hartmann or pyramid. Real-time computer (RTC) prototyping activities are also ongoing, as part of the H2020 Green Flash project, which, more broadly, aims at prototyping RTC for complex AO systems such as MCAO. These two activities are planned to be coupled to build a SCAO prototype for MICADO. The last prototyping is concerning the MICADO coronagraphic mode and is planned to begin in 2016.

On the AO side, simulations activities are being performed to guide the choice of the SCAO sensor, in addition to the prototyping activity, to start the dimensioning of the WFS and to draw an AO error budget. These simulations are performed with COMPASS, our GPU-based end-to-end simulation software. We made a major upgrade of this software, developing a user interface layer in Python in replacement of the Yorick one. New functionalities have also been implemented to better match the E-ELT configuration (M1 pupil, co-phasing errors, etc). Simulations are also starting for the MICADO coronagraphic mode to derive a first assessment of the performance of this mode.

Finally, opto-mechanical preliminary design is in progress. The SCAO WFS has been allocated a volume, the so-called "Green Doughnut", that fits the two configurations, MICADO in standalone mode and when coupled to MAORY. In this volume will be implemented the SCAO WFS, its dedicated calibration unit and the three MAORY NGSs.

We will present here first the MICADO SCAO top-level specifications, the current SCAO prototyping activities, the concepts contemplated for SCAO subsystems (WFS, RTC) as well as the current preliminary design of the MICADO SCAO system.

9909-11, Session 3

Designing the METIS SCAO and LTAO systems

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METIS, the Mid-infrared E-ELT Imager and Spectrometer, will be providing high-sensitivity imaging and high-resolution spectroscopy in the mid-infrared (3-19 micrometer) to the E-ELT. In order to achieve the exceptional performance required by its driving science cases, exoplanets and proto-planetary disks, METIS will be featuring two Adaptive Optics (AO) systems—a first-light Single Conjugate Adaptive Optics (SCAO) system, complemented by a Laser Tomographic Adaptive Optics (LTAO) system, most likely, a few years after first light. METIS, being one of the three first light science instruments on the European Extremely Large Telescope (E-ELT), will be one of the first instruments using the integrated deformable mirror of the E-ELT for its Adaptive Optics (AO) correction.

The internal SCAO system designed to maximize the performance for bright targets and has its wavefront sensors (WFSs) build inside the METIS cryostat to minimize the number of warm surfaces towards the science detectors. Although the internal dichroic will reflect all light short wards of 3 micrometers towards the WFS, only the IR light will most likely be used,

mainly due to the expected improved performance at longer wavelengths for the WFS. A trade-off has been made between both visible versus infrared wave front sensing as well as Pyramid versus Shack-Hartmann, under various observing conditions and target geometries, taking into account performance, target availability, reliability and technology readiness level. The base line for the SCAO system is to minimize system complexity, thereby ensuring system availability and reliability even under first-light conditions.

Since the SCAO system will require a bright guide star near the science target, it can only be used for a limited number of targets. The LTAO system, consisting of up to 6 LGS and up to 3 low-order NGS WFS and located outside the cryostat, is designed to increase the sky coverage on arbitrary targets to >80%. Investigations are ongoing if the internal SCAO system can be used as either a Low-Order WFS or metrology system.

This paper describes the most recent developments of the SCAO and LTAO designs.

9909-12, Session 4

Final two stage MOAO on-sky demonstration with CANARY

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In 2007, the project developing an on-sky demonstrator for multi-object adaptive optics (MOAO) was initiated. This was in the framework of the pre-phase A study of the EAGLE instrument, a MOAO-assisted IR spectrograph for the observation of distant galaxies. At that time, MOAO was regarded as an uncertain, challenging technique by the European community. This led the University of Durham and Paris Observatory to propose to install an MOAO pathfinder called CANARY on the William Hershel Telescope in La Palma. The programme for setting up the full complete experiment was established through 3 main phases of increasing complexity, starting from the demonstration of open-loop tomography on natural guide stars (NGS) in 2010, to the open-loop tomography behind a wide-field closed-loop first stage using mixed laser guide star (LGS) and NGS control.

First images were successfully obtained in July 2010. Then, MOAO coupling 3 NGS and 4 Rayleigh LGS in open loop in 2013 and laser tomography AO (LTAO) in 2014 were demonstrated. In 2015 CANARY obtained the final results as a two-stage system that mimics the future E-ELT: a LTAO-driven woofer based on 4 LGS delivers a ground-layer compensated field to a figure-sensor locked tweeter DM, that achieves the final on-axis tomographic compensation.

CANARY has four Rayleigh LGS wave-front sensors (WFS), three off-axis NGS WFS, two figure sensors, and a so-called truth sensor that do not take part to the correction, but allows us to assess the error breakdown, perform calibrations, and close a classical SCAO loop for reference images. The total number of slopes and actuators crunched by the real-time computer (RTC) went from 288x54 in 2010 to 2042x297 in 2015, a factor of 40 ahead, while the control law went from the simplest of all correctors in 2010 to a rather complex mixed LGS-NGS LTAO pseudo open-loop woofer control completed by a differential tomographic open-loop figure-locked tweeter control in 2015. All this was accompanied by an increase of efficiency of the instrument, from 50 to 200 files archived per night, now processed during the night as they are produced by an automated dedicated pipeline.

We will present the overall system, the control strategy and an overview of its on-sky performance, as well as the ensemble of tools and techniques that were used to assess, at each phase of the project, the wave-front error breakdown.

The perspective for the new E-ELT project of multi object spectrograph, so-called MOSAIC, will be given.

9909-13, Session 4

Keck planet imager and characterizer (KPIC): concept and phased implementation

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The Keck Planet Imager and Characterizer (KPIC) concept is a cost-effective proposed upgrade to the Keck II adaptive optics system, building on the lessons learned from the extreme-AO systems (ExAO: P3K, SPHERE, GPI, SCExAO, MagAO) that will mature system-level and critical components for future segmented ground and space-based instrumentation (e.g. TMT, HDST). The advent of fast low-noise infrared cameras (e.g. IR-APD/MKIDS), the rapid maturing of efficient wavefront sensing techniques (e.g. Pyramid/Zernike), small inner working angle coronagraphs (e.g. vortex, HLC, APP, PIAA) and associated low-order wavefront sensors, as well as recent breakthroughs in high contrast Doppler imaging techniques, open new avenues complementary to first and second-generation ExAO systems. For instance, ExAO in the infrared enables the search and characterization of planetary systems around cool and red M-dwarfs.

The KPIC concept consists of a set of upgrade modules to the Keck II AO system: 1- a Pyramid infrared wavefront sensor (IR WFS) using the latest low-noise IR-APD detector technologies from SELEX ES (see P. Wizinowich et al. for more details, this conference) with an optional high-order deformable mirror, 2- a state-of-the-art starlight suppression device (e.g. the vortex coronagraph, see O. Absil et al., and G. Ruane et al. for more details, this conference), and 3- a fiber-injection unit (FIU) to link the diffraction limited output of the AO system and coronagraph to the Keck II high-resolution infrared spectrograph NIRSPEC (R~37,000 post upgrade). The fiber injection unit contains its own infrared tracking camera and calibration source to allow precise guiding, positioning and injection in the J, H, K or L-band single mode fibers. The choice of monomode fibers ensures modal noise suppression and minimal contamination from the sky background, which is critical for precise spectroscopy and radial velocity measurements. The new AO-fed FIU will enable Doppler imaging of exoplanets and precise radial velocity measurements in the infrared.

KPIC showcases a unique combination of infrared sensing extreme adaptive optics high contrast imaging and high-resolution spectroscopy, integrated at the system level for optimal exoplanet signal extraction around cool stars. The KPIC concept was submitted to the Keck Science Steering Committee as a white paper in June 2015. The KSSC recommended the demonstration of IR WFS technologies, and the implementation of the fiber injection unit. Here, I will report on each element not covered elsewhere in this conference.

9909-14, Session 4

Coronagraphy with two PSFs

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We present on-sky results from our vector Apodizing Phase Plate coronagraph deployed inside MagAO/Clio at the 6.5-m Magellan Clay telescope. The vAPP consists of a single optic with patterned liquid crystals that is located in the filter wheel in the reimaged pupil plane. By superimposing a grating pattern on the coronagraphic phase pattern, the vAPP produces two complementary coronagraphic PSFs with dark holes. The multi-layer liquid crystal pattern furnishes efficient coronagraphic observations for an extremely wide wavelength range of 2-5 microns (KLM bands). Leakage terms due to retardance offsets of the liquid crystals form a third, unsaturated non-coronagraphic PSF in between the coronagraphic PSFs, suitable for photometry and astrometric calibration of substellar companions. On-sky observations show a small amount of non-common path error in the form of primarily trefoil. Such an odd-mode phase aberration induces an imbalance in the intensity of the speckle structure inside the dark holes of the two PSFs, but it leaves intact the symmetry of this structure if the amount of aberration is small. Hence, we can use one PSF to clean up the other, and we employ a simple rotation-subtraction algorithm with an optimized scaling factor to subtract quasi-static speckles inside the dark holes. We demonstrate that with such a data-reduction approach, the vAPP coronagraph at MagAO delivers a 5-sigma contrast of ~1E-5 for 2.5-7 lambda/D. We introduce more advanced methods to extract wavefront information from the two (or three) PSFs to provide focal-plane wavefront sensing.

9909-15, Session 4

The rapid transient surveyor

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The next decade of astronomy will be dominated by large area surveys: ground-based optical transient surveys, e.g., LSST, ZTF and ATLAS and space-based exoplanet, supernova, and lensing surveys such as TESS and WFIRST will join the Gaia all-sky astrometric survey in producing a flood of data that will enable leaps in our understanding of the universe. There is a critical need for further characterization of these discoveries through high angular resolution images, deeper images, spectra, or observations at different cadences or periods than the main surveys.

The Rapid Transient Surveyor (RTS) is a proposed rapid-response, high-cadence facility on the U. of Hawaii 2.2-m telescope on Maunakea, and will uniquely address the need for follow-up characterization of an extensive number of transient objects by combining an excellent observing site with access to the Southern Hemisphere, the unmatched efficiency of the Robo-AO system, and copious available time on the host telescope. This will enable the high-acuity and sensitive spectral follow-up observations of tens of thousands of objects in mere months.

RTS will comprise an upgraded version of the Robo-AO robotic laser adaptive optics (AO) system: using a 492-actuator MEMS deformable a mirror and a UV-optimized EMCCD wavefront sensor camera that has a 2kHz framerate with <0.3e- of readnoise. The system will respond quickly to target-of-opportunity events, minimizing the time between discovery and characterization, and will interleave different science programs with its intelligent queue. RTS will exploit Maunakea's superior observing conditions to routinely acquire simultaneous-multicolor images with an acuity of 0.07-0.10" across the entire visible spectrum (20% i-band Strehl in median conditions and 7% g-band Strel in 25th percentile conditions) and <0.16" in the near infrared, and to detect companions at a contrast ratio of ~500 at 0.5". In addition to the two visible-light EMCCD cameras (for broad and narrowband imaging) and photon-counting infrared camera (based on a SAPHIRA array), the system will include a high-effiency prism integral field unit spectrograph: a spectral resolution of 70-140 over a total bandpass of 850-1830nm with an 8.7" by 6.0" field of view (0.15" spaxels). For the spectrograph, the AO correction boosts the infrared point-source sensitivity against the sky background by a factor of nine, giving the UH 2.2-m the infrared sensitivity of a 6.3-m telescope without adaptive optics.

Our primary RTS science program is to map the dark matter distribution in the z < 0.1 local universe with ten times better accuracy and precision than previous experiments. We will use the Asteroid Terrestrial-Impact Last Alert System (ATLAS) to discover several thousand SNIa per year using automatic detection routines, and follow discoveries with triggered observations with the RTS spectrograph. ATLAS will measure SNIa peak brightness, and decline rates, and the RTS observations will measure reddening by dust, confirm SN type and confirm approximate redshifts of the host galaxies. This unique combination of automated detection and characterization of astrophysical transients during a sustained observing campaign will yield the necessary statistics to precisely map dark matter in the local universe.

9909-76, Session PSun1

Commissioning and first light results of an L'-band vortex coronagraph with the Keck II adaptive optics NIRC2 science instrument

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More than 2000 exoplanets have been discovered to date and yet only for a small fraction of exoplanets has it been possible to acquire direct images. The reason for this lies in the extraordinary technological challenge associated with the large flux ratio between the host star and its planets as

well as the small angular separation between star and planets. To achieve exoplanet direct imaging we inevitably require high contrast imaging systems capable of suppressing the stellar light fed by high angular resolution systems. Nearly all high contrast imaging systems rely on the use of a coronagraphic system and among all the families of coronagraphs the vortex coronagraphs have been gaining extensive credit as one of the most promising solutions due to their excellent properties in terms of very small inner working angle, high transmission, clear 360° discovery space and ease of implementation in existing coronagraphic systems. This latter feature has allowed the deployment of vortex coronagraphs in systems originally designed and built as classical Lyot coronagraphs. Over the last couple of years this has been the case for vortex coronagraphs with different infrared instruments on 8-m diameter monolithic primary mirror class telescopes: VLT, LBT and Subaru.

We present the details of the commissioning of an Annular Groove Phase Mask (AGPM) vector vortex coronagraph with the Adaptive Optics (AO) fed NIRC2 instrument at the segmented 10-m diameter Keck II telescope. This vortex operates in the L' band not only in order to take advantage from the favorable star/planet contrast ratio when observing beyond the K band, but also to exploit the fact that the Keck II AO system delivers nearly extreme adaptive optics image quality (Strehl ratios values near 90%) in L' band.

In this paper we will present the requirements to implement the vortex and the optimization of the Keck II AO system to satisfy these requirements. We will describe the hardware installation of the vortex phase mask during a routine-basis NIRC2 service mission remarking on the ease of installation and the fact that the new vortex phase mask can cohabit with the previously installed classic Lyot coronagraph. We will stress how the success of the project depends on an extensive software development which has allowed the achievement of exquisite real-time pointing control as well as further contrast improvements by implementing speckle nulling to mitigate the effect of static speckles.

During the commissioning of the vortex at NIRC2 part of the team conducted their research programs achieving notable results, some of them briefly presented here to provide evidence of its scientific potential. These science projects are being conducted in parallel to the ongoing commissioning tasks during which we have continued to implement new features.

9909-77, Session PSun1

A versatile natural guide star adaptive optics system for the Eastern Anatolian Observatory (DAG) 4m Telescope

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DAG adaptive optics

Turkey is taking a lift in astronomical science by preparing a new 4-m telescope for infrared observation at high angular resolution. First light is scheduled for 2019. One of the Nasmyth platform will be equipped with a versatile adaptive optics (AO) system, able to offer all options between GLAO and SCAO, to serve the various observation programs of the Turkish astronomical community. Our objective is to make use of the most successful techniques of AO today, i.e. pyramid wavefront sensors (PS) on natural guide stars, tomographic reconstruction, Kalman filtering to compensate for unexpected vibrations, phasor diversity to track and compensate non common path aberrations, and if possible use medium or microsize deformable mirrors. The wavefront sensing and reconstruction scheme is simple: make use of the stars can be found around the target to reconstruct the phase in the volume, then decide how to use this knowledge - either locally, or over some field-of-view. This paper presents these ideas and a study of how these techniques can work together, and most importantly, verify if a PS can be used in open or pseudo-open loop.

9909-78, Session PSun1

The AO system of the 1.5m GREGOR solar telescope: four years of operation

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We present the properties of the AO system of the 1.5m solar telescope GREGOR.

The conventional AO system uses a correlating Shack-Hartmann-Sensor with 10cm subaperture size and a 256-actuator stacked-piezo DM.

The modal controller is based on an optimized Karhunen-Loeve function basis and allows the correction of up to 180 modes.

The control loop frequency of 2100 Hz and an optional modal gain optimizer keep bandwidth errors low.

AO performance results such as modal attenuation factors and power spectra as well as practical experience based on the last years of operation are presented.

A rececently installed alternate wavefront sensor with 24cm subaperture size and an EM-CCD camera is used for low light observations such as polarimetric measurements of the solar system gas giants and Venus.

From 2016, an additional narrow-band H-alpha filter will allow this sensor to lock on (off-limb) solar prominences.

Finally a short overview of the MCAO activities and plans concludes the paper.

9909-79, Session PSun1

Status and new developments with the Keck I near-infrared tip-tilt sensor

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The sky coverage and performance of laser guide star (LGS) adaptive optics (AO) systems are limited by the natural guide star (NGS) used for low order correction. This limitation can be reduced by measuring image motion of the NGS in the near-infrared where it is partially corrected by the LGS AO system and where stars are generally several magnitudes brighter than at visible wavelengths. Based on these principles we initiated the Near-Infrared Tip-Tilt Sensor project (NIRTTS, a.k.a. TRICK for Tilt Removal with IR compensation at Keck) to design and implement a near-infrared tip-tilt sensor based on achieving low readout noise via multiple reads of a 2kx2k pixel H2RG-based detector. A plate scale of 0.05 arcseconds/pixel was chosen to provide a 100 arcsecond diameter field.

On November 2013 we started commissioning of TRICK at the Keck I AO system. We have presented updated reports of the integration and performance of TRICK basic operation mode as a barycenter-based centroid TT sensor on Wizinowich et al. (2014) and Rampy et al. (2015). During 2015 TRICK has been transitioning into shared-risk science operation as TRICK main operating mode has nearly completed full comissioning. The first part of this paper details on the on-sky performance and how it compares against the performance achieved with the visible APD-based tip-tilt sensor at Keck 1 AO system. We also present how TRICK is used operationally and some preliminary scientifc results already achieved.

In the second part of this paper we will discuss the enhanced-TRICK project which builds on the TRICK system to provide additional capabilities and performance gains. The TRICK system supports imaging and integral

field spectroscopic science short of K-band and we will be implementing a new dichroic to allow K-band integral field science. The enhanced-TRICK system has the capability to read out multiple regions of interest (ROIs) on the detector and to use the existing visible tip-tilt sensor simultaneously. We are therefore testing the use of multiple NGS to improve performance and sky coverage via reduced angular anisoplanatism and/or better tip-tilt signal-to-noise ratio (SNR). This involves determining how best to optimize the read rates for each NGS and the relative weighting for each NGS tip-tilt measurement in the commands to the tip-tilt mirror. We will also be testing improved tip-tilt algorithms, specifically a correlation algorithm expected to improve performance on dim NGS due to its low sensitivity to background effects. Overall we are also studying how to optimize the system's performance and how to make use of this knowledge 0operationally.

9909-80, Session PSun1

Infrared differential imager and spectrograph for SPHERE: very high-contrast performances analysis based on SPHERE/GTO observations

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SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research) is a second-generation instrument for the VLT, optimized for very high-contrast imaging around bright stars. Its primary goal is the detection and characterization of new giant planets around nearby stars, together with the observation of early planetary systems and disks. The Infrared Dual Imager and Spectrograph (IRDIS), one of the three SPHERE subsystems, providing dual-band imaging in the near-infrared, among with other observing modes such as long slit spectroscopy, classical imaging and infrared polarimetry, is able to achieve extremely high contrast with the help of extreme-AO turbulence compensation, coronography, exceptional image quality, very accurate calibration strategies and advanced data processing. The SPHERE garanteed time Survey observations has started early 2015, and so far approximately 150 stars have already been observed. IRDIS achieves the sensitivity and resolution compatible with detection planetary companions with separations of 0.2" to 1" around a very large set of selected stars. We will review the high contrast performances achieved at this stage of the GTO observations with IRDIS. In particular we will present an analysis of the level of contrast achieved and relate these performances to the star magnitude, the atmospheric conditions, and the strehl ratio. We will also show typical detection limits for extra-solar planets and for circumstellar disks. We will conclude with highlighting few excquisite astrophysical results obtained with SPHERE/IRDIS.

9909-81, Session PSun1

The ZIMPOL high-contrast imaging polarimeter for SPHERE: polarimetric high-contrast commissioning results

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SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research) is a second generation VLT instrument aimed at the direct detection of exo-planets. ZIMPOL (Zurich Imaging Polarimeter) is the imaging polarimeter subsystem of the SPHERE instrument. During the SPHERE fourth commissioning period (October 2014) we have made deep coronagraphic observations of the bright star alpha Gru (mR = 1.75) to assess the high contrast polarimetric performance of SPHERE-ZIMPOL. We reach contrasts of 10-6 and 10-7 at a radial distances of respectively 7 and 14 lambda/D from the PSF core.

9909-82, Session PSun1

Status of the HARMONI single conjugate adaptive optics module

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HARMONI is a visible and near-infrared (0.47 to 2.45 μm) integral field spectrograph, providing the E-ELT's core spectroscopic capability, over a range of resolving powers from R~500 to R~20000. HARMONI is conceived as a workhorse instrument, addressing many of the key E-ELT science cases. It will exploit the E-ELT's scientific niche in its early years, starting at first light. To get the full sensitivity and spatial resolution gain, HARMONI will work at diffraction limited scales. This will be possible thanks to two adaptive optics systems, complementary to each other. Both systems will make use of the telescope's adaptive M4 and M5 mirrors. The first one is a simple but efficient Single Conjugate AO system (good performance, low sky coverage), fully integrated in HARMONI itself. The second one is a Laser Tomographic AO system (medium performance, very good sky coverage).

The SCAO module consists in a high precision Wave-front sensor [WFS] dedicated to the measurement of turbulence and telescope perturbations, a WFS-path dedicated to the beam shaping (pupil rotation and shifts, modulation, potential atmospheric compensation) and finally a Real-Time computer for Instrument providing a wave-front interface to the telescope for further compensation.

We present in this paper the chosen concept for SCAO module, based on trade-off on available technology, performance, operation and calibration considerations. Some main performance results based on both E2E simulation models as well as fast Fourier simulations are synthesized, including some detailed aspects on WFS capability but also on Telescope perturbations. These last ones are one large contribution to the final performance, and include wind shake effects, spider shape, primary mirror phasing and scalloping effect.

9909-83, Session PSun1

Progress with multi-conjugate adaptive optics at the Big Bear Solar Observatory

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The MCAO system at the BBSO off-axis telescope is the pathfinder system for a future system at the 4-meter off-axis DKIST. Therefore, the MCAO system purposefully has maximal design flexibility. It deploys three DMs, one in the pupil and two conjugated to higher altitudes. The design allows rapid, simple, independent adjustments of conjugate altitudes of the latter two to adapt to changing the turbulence profile ranging from 2-9 km. Either of two DMs are available to accommodate a pupil DM - before or after the high-altitude DMs - to address the relevance of the correction sequence. Wavefront sensing is based on correlating Shack-Hartmann sensors, which can used in various configurations. The optical path has been improved during 2015 to yield satisfying solar images. The MCAO controlled field of view is about 1 arcmin, and the closed loop was able to slightly reduce the wavefront error across the field as compared to the classical AO. We are looking into strategies and modifications, such as decreasing the controlled field of view, to further improve the benefits of MCAO over classical AO. We will report the latest on-Sun results and motivate the design of the system.

9909-84, Session PSun1

In-lab characterization of the DARK-speckle near-infrared energy-resolving superconducting spectrophotometer (DARKNESS)

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The DARK-speckle Near-infrared Energy-resolving Superconducting Spectrophotometer (DARKNESS) is a 10-kilopixel Microwave Kinetic Inductance Detector (MKID) integral field spectrograph developed for high-contrast astronomy applications with Project 1640 and the Stellar Double Coronagraph (SDC) at Palomar Observatory. Leveraging the energy resolution and read-noise-free photon-counting capabilities of optical/near-IR MKIDs, DARKNESS generates data cubes with >1kHz frame rates, which allows for simultaneous spectral and statistical discrimination of faint companions from residual stellar speckles. When interfaced directly with the PALM-3000 adaptive optics system, these frame rates will allow closed-loop focal plane wavefront control for active speckle nulling at >100 Hz. Here we present the in-lab characterization of the completed DARKNESS instrument in preparation for its July 2016 commissioning.

9909-85, Session PSun1

VODCA (the vortex optical demonstrator for coronagraphic applications) and first results with L-band AGPMs

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We are developing at the University of Liège (Belgium) a vortex coronagraph based on sub-wavelength gratings (SGVC). The first generation of these SGVCs is known as the Annular Groove Phase Mask (AGPM), a charge-2 vector vortex phase mask. Etched onto diamond substrates, the AGPMs are produced at Uppsala University. Four of them have now been installed on world-leading diffraction-limited infrared cameras, namely VLT/NACO, VLT/VISIR, LBT/LMIRCam, and Keck/NIRC2. As a part of the VORTEX project, it has become crucial to have at the University of Liège our own dedicated optical bench, VODCA (the Vortex Optical Demonstrator for Coronagraphic Applications), to perform the tests and to assess the quality of the produced components. This high contrast test bench has been developed over the last two years. It operates in the same wavelengths as our AGPMs, i.e., the near- to mid-infrared (between 1 and 5 μm). We use different broad-band and narrow-band filters to cover this wavelength range. Analyzing the results of the AGPM at different wavelengths give us strong indications about the physical characteristics of a single component. This infomation is used to improve the performance of the component by ecthing it again.

In the first part of this talk, I will describe VODCA's layout and some of its key features, such as the possibility to image the pupil, and the recent addition of two polarizers to measure the phase ramp induced by the vortex phase mask. I will also present our automatic procedure to center the AGPM onto the infrared beam. The aberrations are a decisive factor in the best starlight cancellation a coronagraph could achieve. A deformable mirror will soon be integrated in VODCA to first provide a wavefront with the lowest possible amount of aberrations. The deformable mirror will also be used to study how robust the vortex phase mask performance is

against some of the main aberrations (tip/tilt/focus). Others pre-/post coronagraphic concepts, which will be implemented on VODCA, will also be described.

In the second part of this talk, I will report on the performance of the bench in terms of achievable contrast, and show the first results obtained with L-band AGPMs on VODCA.

9909-86, Session PSun1

Preliminary result of the solar multi-conjugate adaptive optics for 1m new vacuum solar telescope

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Solar observation with high resolution in large field of view (FoV) is required for some solar active regions with the typical sizes of 1' to 3'. Conventional adaptive optics could not satisfy this demand because of the atmospheric anisoplanatism. Through compensating the turbulence in different heights, multi-conjugate adaptive optics (MCAO) has been proved to obtain a larger corrected FoV. We had built a multi-direction Shack-Hartmann wavefront sensor (MD-SHWFS) with 7?7 subaperture array and 60 arcsec field of view. The three-dimensional wavefront sensing utilizing atmospheric tomography had been validated by on sky solar observation. Based on this result, a MCAO system including a conventional 151-element AO system and a 37-element AO system with the MD-SHWFS a 37-element deformable mirror conjugated into the 2km to 5km height has been developed. The frame rate of the MD-SHWFS is about 840Hz. In this paper, this MCAO system will be introduced. The preliminary experimental results on the 1m New Vacuum Solar Telescope (NVST) of Full-shine Lake Solar Observatory are presented.

9909-87, Session PSun1

MAORY adaptive optics module for E-ELT: instrument design overview

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MAORY is a post-focal adaptive optics module for the European Extremely Large Telescope (E-ELT) that forms part of the first light instrument suite for the telescope. It enables wide-field diffraction-limited observations with the E-ELT by real-time compensation of the wavefront distortions due to the atmospheric turbulence and to the wind action on the telescope.

MAORY supports the MICADO near-infrared camera by offering two adaptive optics modes: Multi-Conjugate Adaptive Optics (MCAO) and Single-Conjugate Adaptive Optics (SCAO). Development of the SCAO mode is a joint endeavour between the MAORY and MICADO instrument teams.

The MCAO mode is required to achieve high quality and spatially uniform adaptive optics compensation over the full MICADO field of view; sky coverage, i.e. the capability to achieve such a level of performance over a large fraction of the sky, is also an essential feature. The SCAO mode is required for peak adaptive optics performance, rather than uniformity over the field or sky coverage.

In the MCAO mode, wavefront sensing is performed by real-time analysis of the light from six artificial Laser Guide Stars and of three Natural Guide Stars, respectively for the measurement of high and low-order wavefront perturbations; wavefront compensation is achieved by one or two adaptive mirrors in MAORY, which work together with the telescope adaptive and tip-tilt mirrors M4 and M5 respectively.

In the SCAO mode, wavefront distortions are measured by a single Natural Guide Star wavefront sensor and compensated using the telescope M4 and M5 mirrors, while the adaptive mirrors inside MAORY are kept fixed at their reference shape.

MAORY also offers provision for a second port for a future instrument, as yet undefined.

From the opto-mechanical point of view, MAORY is a large instrument, with typical size of 8-10 meter, including an optical relay which creates an image of the telescope focal plane at the entrance of the client instruments. The relay also hosts the two adaptive mirrors for the MCAO mode. The instrument is supported by an hexapod structure which is fixed onto the E-ELT Nasmyth platform.

The phase B of the MAORY instrument project is in progress. Consolidation of the baseline instrument design is underway, taking into account scientific performance requirements, interface constraints and technology readiness of crucial hardware components.

A system level overview of the instrument preliminary design and of its expected performance is presented in this contribution.

9909-88, Session PSun1

Adaptive optics capabilities at the Large Binocular Telescope

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The Large Binocular Telescope (LBT) is unique in that it has two permanently mounted adaptive secondary mirrors (ASM) to control the wavefront correction as measured by different wavefront sensors located at different Gregorian focal stations of the telescope. The First Light Adaptive Optics (FLAO) systems are located at the Front Bent Gregorian (FBG) foci and provide correction for the two LUCI NIR imagers/spectrographs; the ARGOS wavefront sensors are also accessed via the FBG and provide ground-layer correction for the two LUCIs; the two Large Binocular Telescope Interferometer (LBTI) systems are located at the Center Bent Gregorian stations and provide correction for the LBTI Optical Bench including the beam combiner; and the Rear Bent Gregorian stations are being prepared for the installation of LINC-NIRVANA. In addition to the overview of the current status and future plans for the AO systems and the ASMs, we will also discuss the current and planned AO fed instrumentation outlining the scientific capabilities of the LBT AO systems ranging from narrow-field visible light imaging and coronagraphy to wide-field enhanced seeing imaging and spectroscopy in the NIR to 23m baseline diffraction-limited imaging in the NIR and MIR.

9909-89, Session PSun1

Reshaping and polishing the GeMS MCAO system

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GeMS, the Gemini South MCAO System, has now been in operation for 3 years with the near infrared imager GSAOI. We first review the performance obtained by the system, the science cases and the current operational model. In the very near future, GeMS will undergo a profound metamorphosis, as we will integrate a new NGS wavefront sensor called NGS2, replace the current 50W laser with a more robust one and prepare for a new operational model where the system will be operated from the base facility. Along this major evolution, we are also presenting several improvements on the loop control, calibrations and automatisation of this complex system. We discuss here the progress of the different upgrades and the consequence we are expecting in terms of performance and operational efficiency.

9909-90, Session PSun1

Adaptive optics operations at the Large Binocular Telescope Observatory

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The goal for the adaptive optics systems at the Large Binocular Telescope Observatory (LBTO) is for them to operate fully automatically, without the need for an AO Scientist except on-call, and to be able to be run by the observers and/or the telescope operator. In its initial operational configuration, the AO systems would optimally close the loop using parameters acquired from a look-up table. These parameters determined the maximum number of modes and frame rate when using guide stars of differing magnitude. After the AO systems were closed, a procedure to optimize the loop gains for the observing conditions was applied. If the observing conditions changed significantly the gains would have to be changed manually or else the loop would open. If the loop opened, the observing sequence would have to be restarted from the beginning.

To improve the observing efficiency, the following have been implemented. Firstly, a modified state machine which permits the loop to be reclosed without returning to the beginning of the sequence. And secondly, the application of an algorithm which dynamically computes the optimal gain for changing observing conditions. Additionally, we have implemented a non-common path aberration procedure to remove quasi-static aberrations not sensed by the pyramid wavefront sensor. The software permitting these updates is now uniformly implemented on the two FLAO systems as well as the two LBTI/AO systems.

We have also implemented an enhanced seeing mode operation which closes the loop with ~ 10 modes which improves the natural seeing by ~ 2x-3x across fields up to 4 arcminutes diameter.

9909-91, Session PSun1

GRAAL on the mountaintop

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GRAAL is the adaptive optics module feeding the wide-field IR imager HAWK-I at the VLT observatory. As part of the adaptive optics facility, GRAAL is equipped with 4 Laser-guide star wave-front sensors and provides a large field-of-view, ground layer correction system to HAWK-I.

After a successful testing in Europe, the module has been re-assembled in Chile and installed at the Nasmyth-A platform of Yepun, the fourth Unit telescope of the observatory. We report on the installation of GRAAL on the mountain and on its first testing in stand-alone and on-sky.

The system is now operational and waiting for the installation of the deformable secondary mirror to perform fully fledged tests.

We address the performance of the system, including

- verification of a large co-rotator tracking the pupil for the four LGS-WFS,

- positioning of the tip-tilt sensor on-sky,
- interaction of the system with the preparation tools necessary for observation: the selection of a TT star on a large 13 arcmin diameter annulus must be combined with the avoidance of telescope probes shading
- L3-CCD, CCD-220 based WFS camera operation and performance characterization

9909-92, Session PSun1

Solar adaptive optics for 1m new vacuum solar telescope

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Adaptive Optics (AO) has become the requisite equipment of the ground-based large solar telescope to correct the wavefront aberration induced by the atmospheric turbulence. Two generation solar AO systems, one is the 37-element low-order AO system with 2100Hz frame rate and the other is 151-element high-order AO system with 3500Hz frame rate, were successfully developed in 2013 and 2015 respectively. In this presentation, the development of the two AO systems for 1-m New Vacuum Solar Telescope (NVST) at Fuxian Solar Observatory (FSO) will be introduced and the solar high resolution observational results are presented.

9909-94, Session PSun1

LGSAO 10th anniversary: recent and future upgrades for Subaru adaptive optics

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The Subaru laser guide star adaptive optics (LGSAO) will celebrate this summer the 10th anniversary of its first light. Since the last decade, LGSAO has been an integral part of Subaru telescope instruments but also one of the most efficient adaptive optics on MaunaKea.

During this meeting, we will present the recent optimizations and upgrades of the instrument including the new bimorph deformable mirror integration, the AO telemetry analyzer and the transponder-based aircraft detector (TBAD), which will permit to increase the number of science night allocated for Laser guide star observations.

During this meeting, we will also take the opportunity to present the future Subaru GLAO project, Ultimate Subaru, with its adaptive secondary mirror and the new 20W laser which will replace our actual system in the next few years.

9909-95, Session PSun1

High resolution sodium layer plume profiles and parameters for the CANARY experiment

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The column density of the sodium layer is of vital importance for LGS assisted AO instrument simulation, development and operation. This becomes even more important for Extremely Large Telescopes where the laser launch can be far from the AO wavefront sensor subapertures, resulting in a substantial perspective elongation of the sodium spot. Variations in the sodium layer can cause significant variation in the wavefront measured from an LGS, meaning the properties of the sodium layer must be well understood and characterised. This is not only critical during operation, but must be investigated during instrument design phases also.

CANARY is the tomographic AO testbed on the 4.2m William Herschel Telescope, La Palma. The latest upgrade to the CANARY system allows observations of a sodium LGS, launched from a point 40 m off-axis. In addition to observing the sodium LGS with the CANARY WFSs, the sodium profile is also monitored from the 2.5m Isaac Newton Telescope. The INT is approximately 420m further off-axis resulting in a sodium LGS elongation of over 5 arc minutes. This allows a high-vertical resolution profile of the sodium LGS to be measured synchronised with the wavefront sensors of CANARY.

Here we show the results from the first commissioning study in La Palma, examine the appearance of the sodium elongation on realistic wavefront sensors and compare the sodium statistics to published data. Finally we describe how the measured sodium profile could be used with the CANARY system to improve LGS AO performance.

9909-96, Session PSun1

Performance monitoring of an AO instrument: the case of SINFONI

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We present how we perform the characterisation of the performances of an instrument at the Paranal Observatory, how we follow the history line of its key parameters and detect possible problems, taking the example of the AO-assisted SINFONI instrument. We will make a review of the health check performed on the instrument, with analysis of the long term trends. We will analyse the reliability of the data recorded during daily calibrations and night operations, and evaluate their sensitivity and relation to external parameters. This study of the trends of the key parameters of the instrument provides useful analysis and monitoring to determine when an instrument eventually starts to degrade or to trace in time the different events in its maintenance.

One can also determine when a major intervention or upgrade of the system might be necessary. In this eventuality, the long term monitoring can be used to determine the elements to be upgraded, where to focus the efforts to maximise the gain versus the work performed, and provides useful information on the status of the instrument prior to the intervention giving a zero point. The continuous monitoring of all the key parameters and the obtained history line is a valuable information to determine across time the changes obtained through an upgrade.

9909-97, Session PSun1

CIAO: wavefront sensors for GRAVITY

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GRAVITY is a near-infrared instrument that will combine the light of the four unit or four auxiliary telescopes of the ESO Paranal observatory in Chile. The major science goals of GRAVITY are the observation of objects in close orbit around, or spiraling into the black hole in the Galactic center with unrivaled sensitivity as well as studies of young stellar objects and evolved stars.

In order to cancel out the effect of atmospheric turbulence for each of the unit telescope and to be able to see beyond dusty layers, GRAVITY needs infrared wavefront sensors when operating with the unit telescopes. Therefore GRAVITY consists of the Beam Combiner Instrument (BCI) located in the VLTI laboratory and a wavefront sensor in each unit telescope Coude room, thus aptly named Coude Infrared Adaptive Optics (CIAO). The BCI has been recently installed at Paranal and testing with the auxiliary telescopes is ongoing. The first results are very promising.

The CIAO wavefront sensors are built under the responsibility of the Max Planck Institute for Astronomy (MPIA) and shall be installed at Paranal between February and September 2016. Lessons learned during the prototyping phase were applied to the production systems of CIAO to facilitate a more streamlined and stable alignment and operation at Paranal. In close cooperation with ESO and the GRAVITY consortium under the lead of the PI institute MPE (Max Planck Institute for Extraterrestrial Physics), the MPIA team plans to finish the first CIAO system by end 2015 to be ready for shipment to Paranal observatory in early 2016.

This presentation will give an overview of the design of the CIAO production systems, the Assembly, Installation and Test process at MPIA and the Assembly, Installation and Verification activities at Paranal.

By the time this conference will take place, two of four wavefront sensors should have been installed at Paranal allowing already a first test together with the Beam Combiner Instrument.

9909-98, Session PSun1

System tests and on-sky commissioning of the GRAVITY-CIAO wavefront sensors

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GRAVITY is a near-infrared intererometric instrument that allows astronomers to combine the light of the four unit or four auxiliary telescopes of the ESO Very Large Telescope in Paranal, Chile. GRAVITY will deliver extremely precise relative astrometry and spatially resolved spectra. In order to study objects in regions of high extinction (e.g. the Galactic Center, or star forming regions), GRAVITY will use infrared wavefront sensors. The suite of four wavefront sensors located in the Coudé room of each of the unit telescopes are known as the Coudé Integrated Adaptive Optics (CIAO). The CIAO wavefront sensors are being constructed by the Max Planck Institute for Astronomy (MPIA) and will be installed and commissioned at Paranal between February and September of 2016. This presentation will focus on system tests performed in the MPIA adaptive optics laboratory in Heidelberg, Germany in preparation for shipment to Paranal, as well as on-sky data from the commissioning of the first instrument. We will discuss the CIAO instruments, control strategy, optimizations, and performance at the telescope.

9909-99, Session PSun1

Status of Hida solar adaptive optics system and experiment of tomographic wavefront sensing

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We are developing a solar adaptive optics (AO) system for the 60-cm domeless solar telescope of the Hida Observatory, Japan. The optical path of the AO system is alternative to a horizontal or vertical spectrograph by

changing mirror combinations. Such an optics design will allow various solar observations, such as high-dispersion spectroscopy, narrow-band imaging and high-precision polarimetry. The AO system has a deformable mirror with 97 piezo-actuators, a Shack-Hartmann (SH) wavefront sensor with a 10x10-array microlens and a CMOS camera with 4000 fps. We reported the preliminary status of the AO system in the 2014-SPIE conference.

We conducted computer simulations to analyze performances of our AO system, and then found two major points to be improved. One of them was the use of Karhunen-Loève (KL) functions instead of the Zernike polynomials in the expansion of wavefront phases. That greatly reduced fitting errors near the aperture edge, in particular, when using a large number of orthogonal functions. The other point was the reduction of the total time of computation and exposure. We simulated AO behaviors with various parameters, such as image size, the number of subapertures and the field of view (FOV) per subaperture, and evaluated the residual wavefront errors. We then determined the best parameters for our AO system, but not yet apply them to the true system at time when we are writing this abstract. In the coming SPIE conference, we will show effects of the above improvements.

In parallel to improving the AO system, we are introducing a ground-layer (GL) AO system and/or a multi-conjugate (MC) AO system in order to widen the FOV to be corrected. Although the GLAO is incapable of realizing the diffraction limit, we decided to develop a GLAO system first because it does not require the addition of a deformable mirror and the modification of optical system. It is necessary to develop a technique of tomographic wavefront sensing for implementing a GLAO system. The sensor must be a SH type, but its subaperutres have a wider FOV than that in conventional sensors. Wavefront sensing using several targets studding over the field implements sampling of wavefront errors on upper layers with several different directions. We are developing software of deriving wavefront errors on the ground-layer and on an upper layer from a tomographic SH image.

We set an experimental tomographic SH sensor on the telescope focus to collect the test data. The sensor was with a 12x12-array microlens and a 512x512-pixel image. The FOV was 54 arcsec per subaperture. We applied our software to the observed data and derived wavefront-phase maps both on the ground-layer and on an upper layer. We are now improving the software code to raise the accuracy of derived phase errors. We will report the detail of the solar tomographic wavefront sensing.

9909-100, Session PSun1

Getting ready for procurement on the NFIRAOS sub-systems, relay optics, and 1st test instrument

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With the official financial commitment of Canada in the TMT project, the work on NFIRAOS is now entering into production phase. The first part of this effort was to grow the production team beyond that invested in the design up to now. Industry was invited to review the existing preliminary design of the various NFIRAOS sub-systems and propose a final detailed version that meets the latest TMT requirements and allows to scope out the integration and test phases. We present here the detailed design of the NFIRAOS main relay optics consisting in a series of 6 large off-axis parabolas (OAPs) mounted on tip-tilt platforms and set to operate at -30 degrees Celsius. Wavefront error simulation for gravity, temperature and pointing adjustment are presented as well as methods for verifying results experimentally. Also presented is the plan for characterizing their optical axis and focal distance in order to guide their integration into the NFIRAOS optical train. We also report on similar work done for the NFIRAOS near-IR high resolution wavefront sensor and acquisition camera subsystem, a standalone instrument that will allow to verify the NFIRAOS performance in each of the three instrument port. NSEN will also serves at the absolute optical and mechanical reference to adjust the beam position and orientation with respect to the large 6 meter mounting interface. Getting the instruments optical axis right on that of NFIRAOS is critical as the field rotates in the instrument ports. NSEN will patrol the FOV at high and low spatial sampling and carry a wavefront sensor to verify performance at high temporal resolution. The NSEN will be the first instrument mounted on NFIRAOS and will thus allow experimenting and refining the approaches and tools that support this critical task. We will report on the NSEN final design and technical challenges of experimentally characterizing the position of a virtual focal plane at tens of microns precision with respect to distant mechanical references with an instrument structure spanning over different thermal zones and set to operate in three orthogonal orientations.

9909-102, Session PSun1

NFIRAOS AO for the Thirty Meter Telescope

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NFIRAOS is the facility Adaptive Optics system for the Thirty Meter Telescope, being designed and integrated at NRC Herzberg in Victoria Canada. In April 2015 the Canadian federal government announced funding for full membership in TMT, and consequently final design and construction activity has ramped up. Approximately a dozen major subsystems in NFIRAOS are under contract with Canadian industry. NFIRAOS is cooled to -30°C and has two deformable mirrors, six laser wavefront sensors, and uses up to three low-order (tip/tilt and/or focus) IR wavefront sensors (OIWFS) on each instrument and up to four guide windows on the science detectors (ODGW) to correct atmospheric turbulence, telescope windshake and quasi-static optical errors. We present recent intensified engineering work and design revisions to NFIRAOS such as a pyramid WFS for a truth wavefront sensor and for NGS-mode observing without lasers, and NFIRAOS' CPU-based real time computer.

9909-103, Session PSun1

Design and development of adaptive optics system in visible and near-IR band for IUCAA 2m Telescope

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Reason of blurring of celestial objects when observing through telescopes are well understood and is correctable by using Adaptive Optics (AO).

AO techniques have been successfully employed in astronomy for more than three decades with large overheads and low efficiency at large telescopes. A reasonably powerful AO system, which works with minimal

overheads and provides good sky coverage, will greatly enhance the scientific capabilities of small and medium sized telescopes.

The Palomar 60-inch telescope currently incorporates Robo-AO, which is the product of a collaborative effort between Caltech, USA and IUCAA, India which started in mid-2009. A second version of Robo-AO called iRobo-AO is currently under development at IUCAA for deployment on the 2m telescope at IUCAA Girawali Observatory.

There are three arms in the AO system. One of them is called wavefront sensing or uv arm. Others are Visible and IR, used for science observation and atmospheric tip-tilt correction. The entire instrument will be mounted at the Cassegrain focus-direct port (behind the primary mirror).

AO system can not correct atmospheric dispersion, which deteriorates resolution normal to horizontal direction. We have designed a rotating type ADC and incorporated in AO system. Generic atmospheric parameter sensitive code is developed to rotate the ADC prisms at any location on the globe, over the wide range of atmospheric condition. Only maximum correctable (atmospheric dispersion) zenith angle gets changed.

To overcome the scarcity of natural guide star, Rayleigh scatter Laser guide star will be created by an independent laser projector system. This system will be attached on side of telescope tube and through periscope system laser will be launched from the back of secondary mirror to create LGS at 10km above the ground. There is a range gate system allows back scattered photons from the LGS to enter in wavefront sensing arm. Range gate system completely works on polarization property. Polarization of LGS light continuously change due to rotation of cassegrain de-rotator to counteract field rotation (Alt- Azimuth types telescope). There is a rotating retarder in range gate system to freeze the polarization of incoming LGS light. The algorithm to freeze the LGS polarization is developed and implemented.

This paper presents the salient features of the Robo-AO concept, optical design, software architecture of ADC & retarder.

9909-104, Session PSun1

NGS WFSs module for MAORY at E-ELT

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We report on the natural guide star (NGS) wavefront sensors (WFS) module for MAORY, the multi-cojugate adaptive optics (MCAO) system for the ESO E-ELT. Three low–order, near–infrared (H-band), Shack–Hartmann sensors provide fast acquisition of the first 5 modes (tip, tilt, focus, astigmatism) on 3 natural guide stars over a 160 arcsec field of view. Three moderate-order (20x20), visible (600-800 nm), pyramid WFSs provide the slow Truth sensing to correct LGS wavefront estimates of low–order modes. These sensors are mounted onto three R–theta stages to patrol the field of view. The module is also equipped with a retractable, on-axis, high–order (80x80), visible, pyramid WFS for the single–conjugate AO (SCAO) mode of MAORY and MICADO. The visible WFSs share the same 80x80 pyramid WFS design. This choice enables also a MCAO NGS capability. Simulations show that Strehl ratios (SR) over 40% are reached with MCAO and three, 2x2 sub-apertures, NIR low-order WFSs working with H-mag=20 reference stars. In SCAO mode, 90% SR for a 8mag stars with a contrast down to 10??5, and 45% SR for a 16mag star, are achieved.

9909-105, Session PSun1

Laboratory results of the AO facility system testing

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For two years starting in February 2014, the AO modules GRAAL for HAWK-I and GALACSI for MUSE of the Adaptive Optics Facility project have undergone System Testing at ESO's Headquarters. They offer four different modes: NGS SCAO, LGS GLAO in the IR, LGS GLAO and LTAO in the visible.

A detailed characterization of those modes was made possible by the existence of ASSIST, a Test bench emulating an adaptive VLT including the Deformable Secondary Mirror (DSM), a star simulator and turbulence generator and a VLT focal plane re-imager.

This phase aimed at validating all the possible components and loops of the AO modules before installation at the actual VLT that comprises the added complexity of real LGSs, a harsher non-reproducible environment and the adaptive telescope control.

In this paper we will present some of the major results obtained and challenges encountered during the phase of System Tests, like the preparation of the acquisition sequence, the testing of the Jitter loop, the performance optimization in GLAO and the offload of low-order modes from the DSM to the telescope (restricted to the M2 hexapod).

The System Tests concluded with the successful acceptance, shipping, installation and first commissioning of GRAAL in 2015 as well as the acceptance and shipping of GALACSI, ready for installation and commissioning early 2017.

9909-106, Session PSun1

Ten years maintaining MACAO-VLTI units in operation in the Very Large Telescope at Paranal Observatory

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The first Multi Array Curvature Adaptive Optics (MACAO) facilities got its first light in UT2 the 18th of April, 2003, at the Very Large Telescope (VLT), Paranal Observatory.

The achievable image sharpness of a ground-based telescope is normally limited by the effect of atmospheric turbulence. However, with Adaptive Optics (AO) techniques, this major drawback can be overcome so that the telescope produces images that are almost as sharp as theoretically possible, i.e., as if they were taken from space.

We summarize some highlights related to the activities needed to keep the MACAO units in operation. Some statistics of problems based on our Action Remedy tool are included, showing how the number of problems has been reduced through the years, although there are still some unsolved ones. Some lessons learned are presented. Corrective and predictive maintenance performed are also shown like the current measurements, transfer functions measurements, thermography pictures, health checks measuring interaction matrix and flat vectors to detect dead APDs or short circuits in the DM, etc. Some forced interventions are presented , for example: the removal of the cabinets from the Coude rooms to avoid

disturbance of acoustic noise and vibrations, the contamination by cooling leaks of the deformable mirrors, and other mirror degradations.

Proper knowledge of the system, good interaction between different discipline groups to perform corrective and preventive maintenance have been key aspects for keeping the MACAOs under control and operative during all these years.

9909-107, Session PSun1

ShaneAO at work: on-sky performance characterization of the adaptive optics system on the Shane 3-meter telescope at Lick Observatory

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The ShaneAO adaptive optics (AO) system and ShARCS near-infrared detector on the Shane 3-meter telescope at Lick Observatory have been in operation since mid-2014. It features a dual-deformable mirror design, 8-, 16- and 30-across wavefront sensing modes, and a dye laser (soon to be replaced by a fiber laser) fed laser guide star system. We report the results of on-sky performance characterization and compare them to prior estimates from optical pipeline modeling. A measured throughout drop in the J-band is investigated and mitigated. The AO system's performance is characterized and presented in detail. Figures of merit from the AO system such as Strehl ratio as a function of guide star brightness and separation are reported.

Why bother with a small telescope at a non-optimal observing site in this era of extremely large telescopes? The Shane telescope and Lick Observatory have been at the cutting edge of AO system research for many years and our current push to demonstrate wind predictive control on-sky to eliminate temporal errors has resulted in significant modifications to the system and many valuable lessons learned that are directly to applicable to all telescopes with AO systems, regardless of size and location. In addition, the utility of a state-of-the-art AO system on a small telescope at a non-optimal observing site is demonstrated.

9909-108, Session PSun1

LINC-NIRVANA MCAO at the LBT: final preparations for first light

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We present an update on LINC-NIRVANA (LN), an innovative, high-resolution infrared imager for the Large Binocular Telescope (LBT). LN employs layer-oriented, natural guide-star, Multi-Conjugate Adaptvie Optics (MCAO) using the Multiple Field of View approach. It delivers a diffraction-limited field of view two arcminutes across, although the current science camera field is considerably smaller. LINC-NIRVANA actually has two identical MCAO systems, one for each of the 8.4 m mirrors of the LBT. The instrument accepts light from both telescopes and is designed for interferometric combination with off-axis fringe tracking. When implemented, this will provide panoramic Fizeau-mode imagery over much of the sky with the 10 mas spatial resolution corresponding to a 23-meter diameter telescope.

Since the last SPIE, the LINC-NIRVANA team has completed lab integration, system level tests, and preparation of the early science plan. This effort culminated in Preliminary Acceptance Europe in May 2015, followed by several months of final testing, disassembly and shipping. We report on these efforts with a focus on laboratory and on-telescope demonstration of the various AO loops and their performance.

LINC-NIRVANA is now in the mountain laboratory at the Large Binocular Telescope undergoing final alignment and testing prior to first on-sky measurements in Fall 2016. An initial craning and fit-test in November 2015 placed the instrument on the telescope itself within the capture range of the LBT bulk optics. Transportation and installation of such a large, complex instrument presented a number of challenges. We report on several technical and logistical issues that are very relevant to the next generation of extremely large telescopes.

Bringing LINC-NIRVANA into operation will involve a hierarchical sequence of internal instrument alignment, followed by alignment of the telescope, and finally on-sky verification and commissioning. We report on this strategy and its interaction with the Early Science plan, which has been designed to maximize the astronomical return of the instrument during this complicated phase between installation and routine operations.

9909-110, Session PSun1

On-sky AO test bench: testing future AO technologies

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We present an AO system specially designed for the 1.6-m diameter telescope of the Observatoire du Mont-Mégantic (OMM). The system has been mounted and tested at the OMM. It can be used to evaluate, directly on the sky, the performance of a number of next generation adaptive optics related technologies. The AO system is based on a 97-actuator ALPAO DM and a high-speed Optocraft Shack-Hartmann wavefront sensor (SHWFS). A beam splitter is located in front of the SHWFS to relay the wavefront to a second optical port which can accommodate a second wavefront sensor. During the initial observing run, the second wavefront sensor was a pyramidal wavefront sensor developed by INO. The AO control is achieve using the ALPAO Core Engine (ACE) software which can be used for closing the loop using one of the wavefront sensor while monitoring the wavefront with the other one. An Andor EMCCD camera is used to record the AO optimized PSF for performance analysis. We present the AO system design and results from tests made in the lab during the opto-mechanical integration. The results from the observing run at the OMM are also presented. The results have demonstrated that this setup can be a highly flexible tool that can allow the direct side-by-side evaluation of new types of wavefront sensors.

9909-111, Session PSun1

Lick Observatory's Shane telescope adaptive optics system (ShaneAO): research directions and progress

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We present a review of the ongoing research activity surrounding the adaptive optics system at the Shane telescope (ShaneAO) particularly the R&D efforts on the technology and algorithms for that will advance AO into wider application for astronomy. We are pursuing the AO challenges for whole sky coverage diffraction-limited correction down to visible

science wavelengths. This demands high-order wavefront correction and bright artificial laser beacons. We present recent advancements in the development of MEMS based AO correction, woofer-tweeter architecture, wind-predictive wavefront control algorithms, atmospheric characterization, and a pulsed fiber amplifier guide star laser tuned for optical pumping of the sodium layer. We present the latest on-sky results from the new AO system and present status and experimental plans for the optical pumping guide star laser.

The new ShaneAO system (the second generation system at Lick Observatory) was commissioned last year with great success. The system uses MEMS high-order AO correction to achieve fine wavefront correction, combined with a woofer DM to provide high dynamic range. The woofer-tweeter control architecture, described theoretically at the previous SPIE Telescopes meeting (9148), has proven on sky to operate extremely well, with the imaging system achieving Strehl ratios near 0.8 in H band with bright natural stars. In order to handle the increased demand for sampling the wavefront on a finer scale, it is necessary to upgrade the laser to one that provides a much brighter guide star. To this end we are planning to commission the fiber amplified sum-freqency laser developed by Jay Dawson at LLNL (SPIE 6102) at the observatory next year (2016). This laser is specifically tuned to enhance the optical pumping of the mesospheric sodium so that the return signal per watt of laser power is optimized. Furthermore it is a flexible pulsed design that enables us to experiment with spectral and pulse formats that simulations have shown potential improvement in return efficiency. With the laser returns we expect (conservatively from nominal format parameters) we expect to achieve near 90% sky coverage for AO in the near IR (J, H, and K) bands. Furthermore, in ongoing experiments we are developing an improved understanding of atmospheric conditions and developing predictive control algorithms that will take advantage of learning the Taylor frozen-flow and quasi-static (dome seeing and telescope aberrations) components. With a combination of predictive control and improved laser return we expect to correct down to visible science wavelengths using the laser guide star. The results of our site testing and progress to the date of the meeting will be presented.

9909-112, Session PSun1

Single-mode fiber coupling measurements using extreme adaptive optics at the Large Binocular Telescope

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A key requirement to enable an astronomical diffraction-limited Doppler spectrograph is efficiently injecting starlight into single-mode fibers (SMFs). Efficient coupling requires a stable, high Strehl ratio incident beam that matches the mode field diameter of the fiber. In preparation for the installation of 'iLocater', a high-resolution SMF-fed spectrograph for the Large Binocular Telescope (LBT), we have commissioned a fiber coupling system that operates behind the LBT "extreme" adaptive optics (AO) system. Using 6 ?m diameter SMF's, we have measured on-sky coupling efficiencies at near-infrared wavelengths (Y-band: 970-1070nm). In addition to exploring coupling efficiencies as a function of natural guide star magnitude and airmass, our system simultaneously records diagnostic data used to identify effects that limit fiber-coupling efficiency. We discuss how on-sky results compare to theory and previous lab experiments, as well as implications for the design of the final iLocater fiber coupling system.

9909-113, Session PSun1

Rejuvenation of a 10 year old AO curvature wavefront sensor: combining obsolescence correction and performance upgrade of MACAO

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The MACAOs curvature wavefront sensors have been designed as a generic adaptive optics sensor for the Very Large Telescope, and six systems have been manufactured and implemented on sky: four installed in the UTs Coude train as an AO facility for the VLTI, and two in UT's instruments, SINFONI and CRIRES. The MACAO-VLTI have now been in use for scientific operation for more than a decade and are planned to be operated for at least ten more years. As second generation instruments for the VLTI were planned to start implementation in end of 2015, accompanied with a major upgrade of the VLTI infrastructure, we saw it as a good time for a rejuvenation project of these systems, correcting there the obsolete components. This obsolescence correction also gave us the opportunity to implement improved capabilities: the correction frequency was pushed from 420 Hz to 1050 Hz, and an automatic vibrations compensation algorithm was added. The implementation on the first MACAO was done in October 2014 and the first phase of obsolescence correction was completed in all four MACAO-VLTI systems in October 2015, and the systems were delivered back to operation. The resuming of the scientific operation of the VLTI on the UTs in November 2015 will allow to gather statistics in order to evaluate the improvement of the performances through this upgrade. A second phase of obsolescence correction has now been started, together with a global reflection on possible further improvements to secure observations with the VLTI.

9909-114, Session PSun1

AOF: standalone test results of GALACSI

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Located at the VLT UT4 Nasmyth B, GALACSI is the Adaptive Optics (AO) module of the ESO Adaptive Optics Facility (AOF) that will correct the optical beam wavefront delivered to the MUSE Integral Field Spectrograph (operating between 465 and 930 nm). It will sense with four 40?40 subapertures Shack-Hartmann wavefront sensors the AOF 4 Laser Guide Stars (LGS), acting on the 1170 voice-coils actuators of the Deformable Secondary Mirror (DSM).

In Wide Field Mode (WFM), the first of its two AO operating modes, GALACSI will enhance the collected energy in a 0.2"?0.2" pixel by a factor 2 at 750 nm over a Field of View (FoV) of 1'?1' using the Ground Layer

AO (GLAO) technique. The Narrow Field Mode (NFM, second mode of GALACSI), provides an enhanced wavefront correction (Strehl Ratio of 5% (goal 10%) at 650 nm) but in a smaller FoV (7.5”?7.5” FoV), using Laser Tomography AO (LTAO. In NFM the near infrared light of on axis science object is detected by a specific infrared truth sensor (IRLOS, InfraRed Low Order Sensor) and used for tip tilt and focus sensing.

GALACSI is an over 1 ton heavy complex AO module, including internal calibration and commissioning units, truth sensors, tracking and closed loop functionalities. Before being ready for shipping to Paranal, the system has gone through an extensive testing phase in Europe, first in standalone mode and then in closed loop with the DSM in Europe. After outlining the technical features of the system, we describe here the first part of that testing phase and the integration with the AOF ASSIST (Adaptive Secondary Setup and Instrument Stimulator) testbench, including a specific adapter for the IRLOS truth sensor. The procedures for the standalone verification of the main system performances are outlined, and the results of the internal functional tests of GALACSI after full integration and alignment on ASSIST are presented.

9909-115, Session PSun1

CHOUGH: spatially filtered Shack-Hartmann wave-front sensor for HOAO

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The CANARY-Hosted Upgrade for High-Order Adaptive Optics (CHOUGH), is a narrow-field of view High-Order Single Conjugate on-sky AO demonstrator, to be placed on the 4.2m WHT telescope. It aims to produce a Strehl ratio greater than 0.5 in the visible region of the spectrum (>640nm). A High-Order wave-front sensor (HOWFS) is a central piece of the experiment; it is a Shack-Harmann with a sampling of 31x31 subapertures across the pupil. A variable aperture spatial filter designed to reduce aliasing for high-spatial frequencies, located at a focal plane preceding the lenslet array. The HOWFS has a quad-cell configuration on the detector with a one-pixel guard ring and 72?m subperture. The detector is a NüVü EMCCD camera, 24?m pixel size, operating at >500Hz. The lenslet array, collimator and relay are commercial off-the-shelf. This was technically challenging due to the small size of the pupil, 2.3mm, and the small optics involved in the design. We present the lab testing results and performance characterisation for the HOWFS obtained in the laboratory.

9909-116, Session PSun1

SHARK-NIR: from K-band to a key instrument, a status update

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SHARK-NIR channel is one of the two coronagraphic instruments proposed for the Large Binocular Telescope, in the framework of the call for second generation instruments, issued in 2014. Together with the SHARK-VIS channel, it will offer a few observing modes (direct imaging, coronagraphic imaging and coronagraphic low resolution spectroscopy) covering a wide wavelength domain, going from 0.6μm to 1.65μm.

Initially proposed as an instrument covering also the K-band, the current design foresees a camera working from Y to H bands, exploiting in this way the synergy with other LBT instruments such as LBTI, which is actually covering wavelengths greater than L’ band, and it will be soon upgraded to work also in K band.

SHARK-NIR has been undergoing the conceptual design review at the end of 2015 and it has been approved to proceed to the final design phase, receiving the green light for successive construction and installation at LBT.

The current design is significantly more flexible than the previous one, having an additional intermediate pupil plane that will allow the usage of coronagraphic techniques very efficient in term of contrast and vicinity to the star, increasing the instrument coronagraphic performance.

The latter is necessary to properly exploit the search of giant exo-planets, which is the main science case and the driver for the technical choices of SHARK-NIR. We also emphasize that the LBT AO SOUL upgrade will further improve the AO performance, making possible to extend the exo-planet search to target fainter than normally achieved by other 8-m class telescopes, and opening in this way to other very interesting scientific scenarios, such as the characterization of AGN and Quasars (normally too faint to be observed) and increasing considerably the sample of disks and jets to be studied.

Finally, we emphasize that SHARK-NIR will offer XAO direct imaging capability on a FoV of about 15”x15”, and a simple coronagraphic spectroscopic mode offering spectral resolution ranging from few hundreds to few thousands.

This article presents the current instrument design, together with the milestones for its installation at LBT.

9909-117, Session PSun1

Adaptive system for solar telescope for working in the conditions of strong atmospheric turbulence

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Command of project on creation of the adaptive optical (AO) system for a solar vacuum telescope (BSVT), working in the Baikal Astrophysical Observatory, are having about 10 years an experience. During this time a few stages of system development are passed, from cross-correlation tracker to the low-order adaptive correction.

Our data of astronomic supervisions in BSVT site talk about that is present strong turbulence in an atmosphere here. To one of feature, created system, there is a necessity of work in the conditions of strong turbulence. Leaning against world experience consider correct above all things to create the two-mirrors AO-system, using tip-tilt of wave- front corrector and flexible (bimorph) mirror with the suitable number of actuators. The algorithms of simultaneous controlling by two active mirrors will be exhaust – by the tip-tilt corrector and flexible bimorph mirror. The leadthrough of statistical analysis of fluctuations of wave-front is assumed, including decomposition in the base of polynomials of Zernike, from data of measurings of wave-front sensor (WFS) for forming of requirements to the parameters of the corrected mirrors.

We are considering the creation of perspective high-speed of wave-front sensor as the following important step. Development of cross-correlation high-res WFS will be carried out for measuring of wave-front in the conditions of strong atmospheric turbulence. Conducted also work on creation of computer model of the AO-system for solar telescope with the use of technologies of the parallel programming. Realization of design of signal will be well-to-do for WFS with the use of multi-layered model of vertical evolution of turbulence intensity. We consider that to the construction of the multi-mirror AO- system it is necessary to befit only after the careful analysis of level of turbulence vertical evolution, as proof-readers of wave-front must be set in planes attended with the most strong layers of atmospheric turbulence.

It information can be got only by a supervision in the telescope site. Therefore constantly conducted work on the set of information of measuring of turbulence in the different seasons of year. Along 2015 a several out-door expeditions were conducted in all seasons for the construction of local seasonal model of turbulence in the point of standing of BSVT. For the receipt of information on the parameters of turbulence the followings measurings devices and equipment are used: differential image motion meter (DIMM) on the base of telescope of MEADE, acoustic weather-station, cross-correlation S-H WFS set on a telescope, a Brandt's sensor. Doppler lidar was episodically used for measuring of wind speed profiles up to the 2 km height. Used, created before, local model of vertical change speed of wind. A task is put – to build the local model of types of turbulence and speed of wind for the BSVT point of standing.

And also to expose the possible going near creation of WFS for the multi-mirror AO-systems controlling. Experience, got at creation of the AO-system for BVST will be further used for the construction the system for new 3-m solar telescope (KST).

A project is financially supported by the grant of the Russian Scienc? Foundation ?15-19-20013.

9909-118, Session PSun1

Adaptive optics on-sky demonstrator for the Anglo-Australian Telescope

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The Australian Astronomical Observatory is currently investigating the use of adaptive optics technologies for the 3.9m Anglo-Australian Telescope at Siding Spring Observatory. It might be that ground-layer or multi-object adaptive optics is beneficial for the Anglo-Australian Telescope (seeing ~1.6"). Key to achieving this goal is an adaptive optics test-bench developed for laboratory experiments and on-sky demonstration. The test-bench provides a facility to demonstrate on-sky natural guide star adaptive optics as well as second stage correction with active injection into single mode waveguides. The test-bench provides wide field access of up to 20 arcminutes for testing our plug-plate distributed wavefront sensors. Data has been collected in a range of seeing conditions where closed-loop corrections were performed. We present the design, results and plans for the adaptive optics on-sky demonstrator.

9909-119, Session PSun1

NFIRAOS in 2015: engineering for future integration of complex subsystems

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The Narrow Field InfraRed Adaptive Optics System (NFIRAOS) will be the first-light facility Adaptive Optics (AO) system for the Thirty Meter Telescope (TMT). NFIRAOS will be able to host three science instruments that can take advantage of this high performance system. NRC Herzberg is leading the design effort for this critical TMT subsystem. As part of the final design phase of NFIRAOS, we have identified multiple subsystems to be sub-contracted to Canadian industry. The scope of work for each subcontract is guided by the NFIRAOS Work Breakdown Structure (WBS) and is divided into two phases: the completion of the final design and the fabrication, assembly and delivery of the final product. Integration of the subsystems at NRC will require a detailed understanding of the interfaces between the subsystems, and this work has begun by defining the interface physical characteristics, stability, local coordinate systems, and alignment features. In order to maintain our stringent performance requirements, the interface parameters for each subsystem are captured in multiple performance budgets, which allow a bottom-up estimate on image plane tolerances for our client instruments. In this paper we discuss our approach for defining the interfaces in a consistent manner and present an example error budget that is influenced by multiple subsystems.

9909-120, Session PSun1

GTC adaptive optics hardware electronics

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The Adaptive optics for GTC is a single conjugated post focal AO system placed in the Nasmyth platform over a static optical table. It has been designed initially for natural guide star and in the later project phase adapted to one Laser guide star. After the AO system, FRIDA instrument will be installed which is a near infrared spectrograph. The AO system is composed of the following subsystems: wavefront corrector, wavefront sensor, structure, calibration system and test camera. This paper presents the hardware electronics to support all this subsystems fulfilling the GTCAO requirements.

9909-320, Session PSun1

First on-sky results with ARGOS

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One year and an half after ARGOS first light, the LBT laser guided ground-layer adaptive optics system has been operated on both side of the Large Binocular Telescope. The system fulfills the GLAO promise and typically delivers an improvement by a factor of 2 in FWHM over the 4'x4' FoV of both LUCI instruments, the two near-infrared imagers and multi-object spectrographs. In this paper, we report on the first on-sky results and analyze the performances based on the statistics collected so far.

We also discuss adaptive optics procedures and the joint operations with LUCI for science observations.

9909-16, Session 5

Review on AO real-time turbulence estimation *(Invited Paper)*

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In this talk, we will review the different methods and results developed for estimating turbulence parameters from Adaptive Optics (AO) real-time data. Contrary to dedicated instrument aimed at measuring turbulence atmospheric parameters, like the MASS/DIMM for instance, the idea is to extract relevant atmospheric parameters directly from the AO telemetry. This has the main advantage that the parameters are extracted in the same line of sight as the science observations, and in the same environmental conditions (e.g. effect of dome, wind etc...)

There are many reasons why getting an information on the turbulence parameters is important for an AO system. First, it might be helpful to understand the delivered performance, and characterize an instrument. It might also be helpful to optimize in real time the numerous AO parameters, in order to get the best performance even when facing changing conditions, and atmospheric parameters can also serve for predictive control. It is also interesting to gather telescope site statistics, and potentially optimize the telescope queue scheduling. Finally, it is always relevant to get such informations when doing post-processing on the science images, and even more when considering PSF estimation across the field and over time. For wide-field AO systems, i.e. those using several Wave-Front Sensors (WFSs), the performance critically depends on a tomographic reconstruction of the turbulence volume. For those systems, having access to the vertical distribution of the atmospheric parameters above the telescope is particularly crucial.

In this paper, we will try to review the different methods and results that have been developed in the past years in order to estimate the required atmospherical and astroclimatical parameters. We will cover different systems, and compare the needs, and approaches developed in order to get the relevant information. Among others, we will review the strategies and techniques tested on a single conjugated AO system, SPHERE from ESO-VLT. We will then look at the methods developed for a Multi-conjugated AO system, installed at the Gemini South telescope, called GeMS. Finally, we will review the strategies developed for two Multi-Object AO systems, namely CANARY, installed at the WHT telescope in Canaries Islands, and RAVEN, an MOAO science demonstrator developed for the Subaru Telescope. For all these systems, we will review the parameters that are estimated, the methods developed, and the results in terms of atmospheric statistical parameters. Over the different atmospheric

parameters, we will especially focus on r0, tau0, Cn2(h), L0(h) and vertical wind amplitude (V(h)) and direction (Vd(h)). We will also explore how those methods can be adapted for future systems like the ESO AOF, or solar MCAO systems.

Finally, we will tentatively extrapolate those results for the future Extremely Large Telescopes, and show how important it is to get an accurate profile estimation for the future Wide-Field AO systems planned for these giants.

9909-17, Session 5

FASS: The full aperture seeing sensor

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We describe a novel technique for the estimation of atmospheric turbulence profiler called FASS (full aperture seeing sensor) based on a low noise CCD detector. The method uses the full aperture of the telescope, with a single CCD detector and a Fourier processing approach that estimates the spatial frequency distribution of the scintillation speckles at the pupil. This frequency approach samples the pupil in rings, making the transformation from space to frequency circular and thus avoiding aliasing or disturbances due to otherwise finite nature of the data. The method provides excellent performance as demonstrated via simulation and on-sky data obtained from small and 1 m class telescopes. The profiles resulting from the technique are compared to those simultaneously obtained with the Durham Stereo-SCIDAR instrument.

It is shown that aspects such as detector exposure time, opto-mechanical stability, detailed spectrum modelling of noise and chromaticity of the stars, must be carefully addressed during the design and calibration stages.

Although the technique is expected to operate in the generalized mode ensuring a minimum speckle size, it is shown that the size of the detector pixel is also a crucial parameter that can severely limit the accuracy at low altitudes. This is especially valid if small or no negative conjugation altitudes are used as the size of the speckles becomes comparable to the pixel size and hence, difficult to disentangle from the detector's noise.

Differences in pixel gains and offsets are effectively corrected, so they don't significantly influence the accuracy of the profile estimation.

Temporal correlations are also shown to provide complementary information no only on the wind speed and direction of layers, but a coarse estimation of their altitude, as the width of correlation peaks moved by the wind depend on the propagation path followed by each one of them. Factors limiting the accuracy of this optional tool are discussed.

Finally, the resilience of the method to strong turbulence regimes (s2 > 0.4) is also addressed and its effect compensated.

9909-18, Session 5

Operational optical turbulence forecast for the service mode of top-class ground based telescopes

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In this contribution we present the most relevant results obtained in the context of a feasibility study (MOSE) undertaken for ESO. The principal aim of the project was to quantify the performances of an atmospherical non-hydrostatical mesoscale model (Astro-Meso-NH code) in forecasting all the main atmospherical parameters relevant for the ground-based astronomical observations and the optical turbulence (CN2 and associated integrated astroclimatic parameters) above Cerro Paranal (site of the VLT) and Cerro Armazones (site of the E-ELT). A detailed analysis on the score of success of the predictive capacities of the system have been carried out for all the astroclimatic as well as for the atmospherical parameters. Considering the excellent results that we obtained, this study proved the opportunity to implement on these two sites an automatic system to be run nightly in an operational configuration to support the scheduling of scientific programs as well as of astronomical facilities (particularly those supported by AO systems) of the VLT and the E-ELT. A complete design for such a system has already been prepared. We are at present in negotiation with ESO for the set-up of a 'demonstrator' to be run on the two sites. The fact that the system can be run simultaneously on the two sites is an ancillary appealing feature of the system. We are, at the same time, responsible for the implementation of a similar automatic system at Mt.Graham, site of the LBT (ALTA Project). Our system/method will permit therefore to make a step ahead in the framework of the Service Mode for new generation telescopes. Among the most exciting achieved results we cite the fact that we proved to be able to forecast CN2 profiles with a vertical resolution as high as 150 m. Such a feature is particularly crucial for all WFAO systems that require such detailed information on the OT vertical stratification on the whole 20 km above the ground. This important achievement tells us that all the WFAO systems can rely on automatic systems that are able to support their optimized use.

9909-19, Session 5

Characterizing and mitigating vibrations for SCExAO

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The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) instrument, under development for the Subaru Telescope, has currently the fastest on-sky wavefront control loop, with a pyramid wavefront sensor running at 3.5 kHz. But even at that speed, we are still limited by low-frequency vibrations. The current main limitation was found to be vibrations attributed mainly to the rotation of the telescope. Using the fast wavefront sensors, cameras and accelerometers, we managed to identify the origin of most of the vibrations degrading our performance. Low-frequency vibrations are coming from the telescope drive in azimuth and elevation, as well as the elevation encoders when the target is at transit. Other vibrations were found at higher frequency coming from AO188's image rotator.

Different approaches are being implemented to take care of these issues. The PID control of the image rotator has been tuned to reduce their high-frequency contribution. We are working with the telescope team to tune the motor drives and reduce the impact of the elevation encoder. A Linear Quadratic Gaussian controller (LQG, or Kalman filter) is also being implemented inside SCExAO to control these vibrations. These solutions will not only improve significantly SCExAO's performance, but will also help all the other instruments on the Subaru Telescope, especially the ones behind AO188. Ultimately, this study will also help the development of the TMT, which will face similar problems.

9909-20, Session 6

Review of AO calibrations, or how to best educate your AO system *(Invited Paper)*

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If the Real-Time Computer is the heart of an AO system, the Wavefront Sensor (WFS) its eyes, the Deformable Mirror (DM) its hands and the control strategy its nervous system, the sum of all those parts is made into a harmonious entity thanks to calibrations.

This paper does not have the ambition to provide an overview of all the currently existing calibration strategies, but rather to focus on a few challenging problems and their recent evolution in the era of adaptive telescopes, mostly based on the experience of ESO's Adaptive Optics Instruments in general and the AO Facility in particular.

Single most important calibration in post-focal AO system, the recording of the Interaction Matrix (IM) between WFS and DM has since long evolved to use fast modulation techniques, has shown to be feasible on-sky and is now almost free from measurements thanks to its pseudo-synthetic generation, mandatory solution in an adaptive telescope. Pseudo- because it requires an unprecedented knowledge of the components' characteristics especially the WFS, DM and the optical registration between the two.

Bigger telescopes and the use of Laser Guide Stars (LGS) also mean that the properties of the system will change in time and thus need to be constantly updated thanks to online diagnosis tools for spot size measurement, atmosphere monitoring, Wavefront Sensing and control optimization.

New loops come into play like the one to minimize LGS Jitter and the one taking over the telescope active optics by means of offloading the DM low orders, and they all require calibration.

More calibration means more time and one has to carefully balance the calibrations that require precious telescope night time, day time or for the best, no telescope time at all.

Their importance sometimes underestimated, calibrations have repeatedly shown to be a vital part in the optimum functioning of present and future AO systems.

9909-21, Session 6

Solving the NFIRAOS calibration puzzle

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NFIRAOS, the first light MCAO system for the Thirty Meter Telescope is currently in its final design phase. In order to meet a very tight end-to-end error budget, many instrumental effects have to be calibrated and compensated for very accurately. These include alignment errors, wave-front errors, actual motion profiles, and sensitivities, for all the operating conditions of the instrument. We have therefore invested a lot of effort in developing a comprehensive calibration plan. In this paper we present the highlights of this plans, including the flow down from the top-level NFIRAOS requirements to the calibration hardware that we have specified for NFIRAOS and the calibration procedures that we have developed. When possible, these procedures are inspired from that developed for the current 8-meter class AO systems and are validated on Henos, the Herzberg NFIRAOS Optical Simulator, which is our scaled down NFIRAOS table-top demonstrator.

One of the calibration tasks that we develop in more details in this paper is the measurement and the correction of the non-common path aberrations, between the NFIRAOS WFSs and the science focal plane. This calibration is particularly challenging (i) because several contributors are outside NFIRAOS, i.e. in the client science instrument and in the telescope, (ii) because the errors to be corrected change continuously, since pupil planes and image planes rotate at different rates as the telescope tracks, and (iii) because measurement sensitivities change as observing conditions, such as seeing, change. As well, field dependent aberrations are particularly important in the context of tomographic AO, and must be addressed carefully. Full calibration performance budgets have been derived in order to make sure the NFIRAOS can be met. These budgets are critical to understand how many measurements need to be obtained to fully cover the full range of parameters while minimizing the time required to perform calibration, especially for telescope effects, since these measurements must be performed during precious sky-time.

9909-23, Session 6

Demonstration of predictive Fourier control for frozen flow wind turbulence on the ShaneAO 3-meter AO system

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We demonstre the application of a Kalman Filter to correct for atmospheric turbulence which can be characterized by Taylor's Frozen Flow Hypothesis. Approximately 30% of the total atmospheric wavefront error is correlated as it translates across a telescope aperture. We demonstrate the application of a Kalman Filter to remove this correllated atmospheric tubulent error, attributed to frozen flow wind. Using the ShaneAO system on the 3-meter telescope at Lick Observatory, we present the first on-sky demonstration of Predictive Fourier Control to reduce the temporal delay error in adaptive optics systems.

We present the results from a demonstration of Predictive Fourier Control on-sky, both in the identification of frozen flow wind velocity vectors, and the correction of those wind vectors using Kalman filters generated based on the latest wind measurements. Our wind identification system uses a Fourier decomposition technique to identify the correlated movement of the atmosphere from WFS telemetry data; the estimated wind vectors are then fed back to the predictive controller. The predictive controller works using a Kalman Filter in the Fourier Domain to filter out the temporal behavior of Fourier modes which show correllated frozen-flow motion. This is the first on-sky application of Predictve Fourier Control to a high-order ($d < 10$ cm) astronomical AO system. We present the impact that our predictive control algorithm has on the residual wavefront error measured in the ShaneAO system, and the effects that this reduction in wavefront error has on the output Strehl of the adaptive optics system.

9909-175, Session 6

Wide field LQG tomographic adaptive optics control with wind-dependent turbulence models

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Tomographic AO optimal control relies centrally on a stochastic model of the turbulence. For wide-field AO static reconstruction (as, e.g., on the CANARY Multi-Object AO instrument [1] or on NFIRAOS [2]), the models used so far incorporate physical priors on turbulence spatial distribution through Cn2 profiles. For Linear Quadratic Gaussian (LQG) control, models based on both spatial priors and temporal dynamics through wind velocity norm in each layer have been proposed [3,4,5]. As for performance, it depends both on the structure of the model on which is based the LQG

controller and on a good tuning of its parameters.

In this work, we propose turbulence models that account for both wind norm and direction in each layer. These new models combine a wind direction-dependent displacement operator with the "boiling turbulence" assumption (i.e. each turbulent mode can be viewed as a stationary stochastic process with known power spectral density). An explicit dynamical Markovian turbulence model of order 2 is obtained, that allows the design of an optimal LQG controller. Several methods that aim at accounting for wind direction in wide-field AO systems have been proposed in recent years. In, e.g., [6], a simple stabilized shift operator is used as turbulence model, while the approach in [7] does not explicitly reconstruct the phase in order to derive a sparse sub-optimal solution. Performance analysis and comparison with the standard MMSE reconstructor and with LQG control based solely on wind norm priors are performed using end-to-end simulations representative of a wide-field AO system.

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9909-24, Session 7

Deformable mirrors development program at ESO

Stefan Stroebele, Elise Vernet, Martin Brinkmann, Gerd H. Jakob, Paul Lilley, Mark M. Casali, Pierre-Yves Madec, Markus E. Kasper, European Southern Observatory (Germany)

Over the last decade, adaptive optics has become essential in different fields of research including medicine and industrial applications. With this new need, the market of deformable mirrors has expanded a lot allowing new technologies and actuation principles to be developed.

Several E-ELT instruments have identified the need for post focal deformable mirrors but with the increasing size of the telescopes the requirements for the deformable mirrors become more demanding. A simple scaling up of existing technologies from few hundred actuators to thousands of actuators will not be feasible or sufficient to satisfy the future needs of ESO. To bridge the gap between available deformable mirrors and the future needs for the E-ELT, ESO started a development programme for deformable mirror technologies. The requirements and the path to get the deformable mirrors for post focal adaptive optics systems for the E-ELT is presented.

9909-25, Session 7

A new driving method for piezo deformable mirrors: open loop control and MOAO made easy

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Usually piezo actuator elements suffer from strong non linearities such as hysteresis. While in closed loop one can easily accomodate for these non linearities ,this becomes a very challenging issue in open loop control which is the case for MOAO applications like the MOSAIC instrument. Previous works were caried out to cancel this hysteresis with charge command instead of voltage command, but this command suffers from low bandwidth and creep (which is a long term deviation in the steady state). Others methods were tried with complex models or mathematical models. All these methods suffer from high complexity, low fidelity and are CPU-time consuming. Moreover they often need an accurate modelization of the piezo element and don't take into account piezo model dispersion, leading to innacurate open loop control.

We have developped a new type of amplifier name the hybrid amplifier which takes the advantages of the voltage command (high speed, no creep, steady state stability) and the advantages of the charge command (hysteresis cancellation). We've demonstrated the aibility to drive hygly non linear piezo elements with a quasi linear behaviour. Moreover this amplifier does not need any knowledge or model of the piezo non linearities, simply we need to know the piezo capacitance which is a very easy measurement.

Using this hybrid amplifier to drive open loop DMs in MOAO systems or other open loop AO systems will give a better accuracy in the wavefront reconstruction and a simpler drive strategy.

9909-122, Session PMon1

Analysis and comparison of the atmospheric parameters retrieved from a XAO instrument with the astro-climatic monitoring system

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Paranal Observatory has a set of astro-climate monitoring instruments such as DIMM, MASS and SLODAR, which are delivering information about the sky quality in terms of seeing, coherence time, high altitude wind speed (200mb) and the vertical profiles of the refractive index structure constant (Cn2) to support the observations. SPHERE is an Extreme Adaptive Optics instrument that uses a Shack-Hartmann wavefront sensor with 40x40 sub-apertures running with a close loop frequency of 1.2KHz. The instrument saves close loop snapshots every minute, and from the data saved the system retrieves the r0 and the cross wind speed. The wind speed is calculated using a cross-correlation based on the peak identification. The knowledge of this parameter is essential to understand the performances of the Adaptive Optics (AO) system, and to optimize its

control laws every minutes. The data from the astroclimatic system monitor will help to correlate the turbulence events with the transverse wind speed retrieved from SPHERE close loop data. The goal of this work is also to compare the different atmospheric monitors with the effective turbulence estimation from the focal plane itself (Differential Tip-Tilt Sensor).

9909-123, Session PMon1

Forecasts of the atmospherical parameters close to the ground at the LBT site in the context of the ALTA project

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In this paper we study the abilities of an atmospherical mesoscale model in forecasting the classical atmospherical parameters relevant for astronomical applications at the surface layer (wind speed, wind direction, temperature, relative humidity) on the Large Binocular Telescope (LBT) site - Mount Graham, Arizona. The study is carried out in the framework of the ALTA project aiming at implementing an automated system for the forecasts of atmospherical parameters (Meso-Nh code) and the optical turbulence (Astro-Meso-NH code) for the service-mode operation of the LBT. The final goal of such an operational tool is to provide predictions with high time frequency of atmospheric and optical parameters for an optimized planning of the telescope operation (dome thermalization, wind-dependent dome orientation, observation planning based on predicted seeing, adaptive optics optimization, etc...). Numerical simulations are carried out with the MESO-NH and Astro-Meso-Nh codes, which were proven to give excellent results in previous studies focused on the two ESO sites of Cerro Paranal and Cerro Armazones (MOSE Project). In this paper we will focus our attention on the comparison of atmospherical parameters forescasted by the model close to the ground with measurements taken by the observatory instrumentations and stored in the LBT telemetry in order to validate the numerical predictions. As previously done for Cerro Paranal (Lascaux et al., 2015), we will also present an analysis of the model performances based on the method of the contingency tables, that allows us to provide complementary key information with the respect to the bias and RMSE (systematic and statistical errors), such as the percentage of correct detection and the probability to obtain a correct detection inside a defined interval of values.

9909-125, Session PMon1

Stereo-SCIDAR atmospheric turbulence profiling: turbulence variability

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Stereo-SCIDAR is a generalised SCIDAR instrument which is used to characterise the atmospheric optical turbulence in terms of Cn2 and wind velocity profile using triangulation between two stars. Stereo-SCIDAR has demonstrated the capability to resolve turbulent layers with the required vertical resolution to support wide-field ELT instrument designs. These high resolution atmospheric parameters are critical for design studies and statistical evaluation of on-sky performance under real conditions.

Stereo-SCIDAR differs from most other SCIDAR instruments in that, instead of overlapping pupil images on a single detector, the image of each star is recorded on a separate EMCCD. Separating the pupil images in this way leads to several advantages, including better signal to noise ratios, larger useable magnitude difference of the target stars and reliable automated wind velocity measurements. The data is analysed and made available to observatory systems in real-time.

Here we review the Stereo-SCIDAR technique and present recent results from the instrument on the Isaac Newton Telescope, La Palma. We report on automated layer by layer variability measurements. The high temporal and spatial resolution of the Stereo-SCIDAR makes it ideal for studying the variability of both the wind velocity and Cn2, key parameters for wide field Adaptive Optics instrument design and operation.

In addition, we are investigating how we can use atmospheric models generated from Global Forecast System data to cross-validate these profiles. These models can then be used to forecast the distribution of optical turbulence above the observatory.

9909-128, Session PMon1

A turbulence profile for the NST MCAO system

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Optical observations of the Sun with higher and higher angular resolution are required for in-depth understanding of the Sun's physics. While today's facility class adaptive optics systems can achieve diffraction limited imaging for 0.7 - 1.6 m telescopes for typical seeing conditions, the field of view that is improved by such systems is often too small to study spatially extended features and events in detail. Multi-conjugate adaptive optics (MCAO) promises to enlarge the corrected field of view and by using the AO data from their multiple wavefront sensors (WFS), the performance of such systems can be significantly improved.

We describe a new turbulence profiler for the MCAO system of the New Solar Telescope (NST) at Big Bear Solar Observatory. The NST MCAO system features three deformable mirrors (DM); two of them are dedicated to compensation of high-altitude turbulence, whereas the third corrects aberrations at the pupil. The opto-mechanical design allows for changing the conjugate plane of the two high-altitude DMs independently between two and nine kilometers. The system also has two correlating Shack-Hartmann WFS. A high-order, narrow-field sensor dedicated to the optical axis, and a low-order wide-field sensor. The wide-field sensor can be subdivided into several guide regions (multi-direction WFSs), allowing a turbulence profile reconstruction, that can be directly estimated from the slopes of the associated WFS (open loop mode) or via pseudo-open-loop slopes when working in closed loop. The profiler can then offer valuable information to adjust the position of the DMs and optimize the tomographic algorithms on-line. Using simulated data we evaluate the profiler for different configurations, i.e. number of guide regions, field of view and number and size of subapertures. Finally, we test the profiler using onsky data from open and closed loop operation that provide estimations for the complete set of turbulence parameters, i.e. Cn2, r0, ?0, wind profile and outer scale profile (L0(h)).

9909-129, Session PMon1

Towards an automatic system for monitoring of Cn2 and wind speed profiles with GeMS

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Wide Field Adaptive Optics (WFAO) systems represent the more sophisticated AO systems available today at large telescopes. One critical aspect for these WFAO systems in order to deliver an optimized performance is the knowledge of the vertical spatio-temporal distribution of the Cn2 and the wind speed.

Previous studies (Cortes et al., 2012) already proved the ability of GeMS (the Gemini Multi-Conjugated AO system) in retrieving CN2 and wind vertical stratification using the telemetry data. To assess the reliability of the GeMS wind speed estimates a preliminary study (Neichel et al., 2014) compared wind speed retrieved from GeMS with that obtained with the atmospherical model Meso-Nh on a small sample of nights. The latter technique is very reliable for the wind speed vertical stratification. The model outputs gave, indeed, an excellent agreement with a large sample of radiosoundings (~50) both in statistical terms and on individual flights (Masciadri et al., 2013).

Such a tool could therefore be used as a valuable reference in this exercise of cross calibrating GeMS on-sky wind estimates with model predictions.

The main results of Neichel et al. (2014) analysis showed that, on a great number of cases, GeMS could reconstruct very good wind speed estimates. At the same time it has been put in evidence, on a number cases, not negligible discrepancies from the atmospherical model. However we observed that these discrepancies strongly decreased or even disappear if the GeMS data reduction could be done with the ‘a priori’ knowledge of the wind speed stratification provided by the model Meso-Nh. The goal of this contribution is two-fold: (1) from one side to confirm conclusions achieved in Neichel et al. (2014) on a more solid statistical sample (data related to ~ 46 nights), (2) from the other side to evaluate the possibility to use, as an input for GeMS, the Meso-Nh estimates of the wind speed stratification in an operational configuration. These estimates can be provided many hours in advanced with respect to the observations and with a very high temporal frequency (order of 2 minutes or less). Such a system would have a set of advantages: (a) to implement inside GeMS a total temporal and spatial coverage of the wind speed over ~ 20 km and all along the night not only in real-time but in advance of a few hours, (b) to improve the detection of the Cn2 vertical stratification from GeMS because a good wind speed estimation would improve the quality of the cross-correlation peaks detection, (c) the possibility to bypass the complex (and not necessarily reliable) procedures necessary to automatize the wind speed estimate of GeMS due to the relatively low vertical resolution of the system.

Such a study can obviously be considered as a demonstrator for multiple operational AO and WFAO systems (AOF, LINC-NIRVANA, RAVEN, ...) of present top-class telescopes and for the forthcoming generation. It might have, therefore, an interest for the AO community well beyond the improvement of GeMS performance.

9909-134, Session PMon1

On-line estimation of atmospheric turbulence parameters and outer-scale profiling

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Estimating the outer scale profile, L0(h), is a highly complex problem. However, its estimation in the context of current very large and future extremely large telescopes is crucial, as it impacts the on-line estimation of turbulence parameters (Cn2(h), r0, ?0 and ?0) and potentially the performance of Wide Field Adaptive Optics (WFAO) systems. In this paper we describe an on-line technique that estimates the outer scale profile using AO loop data available at the facility instruments. It constructs the cross-correlation functions of the slopes of two or more wavefront sensors, which are fitted to linear combinations of theoretical responses for individual layers having different altitudes and outer scale values.

We analyze some restrictions found in the estimation process, which are general to any measurement technique. The insensitivity of the instrument to large values of outer scale is one of them, as the telescope is blind to outer scales much larger than its diameter. Another problem are the contradictory requirements imposed on the length of data for a single estimation: on the one hand, long sequences of minutes or more are necessary to provide sufficient independent data for the method to converge. However, long sequences imply that the stationarity assumption of the turbulence can be broken (turbulence parameters may change during the time span). We propose a method to determine if a satisfactory balance has been achieved to this conflict.

Our method deals effectively with problems such as noise estimation, asymmetric correlation functions and wavefront propagation effects. It is shown that the latter cannot be considered negligible in some cases (e.g. high resolution AO systems, strong turbulence in the free atmosphere especially at high altitudes). The method is applied to the Gemini South MCAO system (GeMS) that comprises five wavefront sensors and two DMs conjugated at the ground and 9Km. Statistical values of turbulence parameters at Cerro Pachón from reduced data acquired with GeMS along three years are shown. Especially interesting are the results for outer scale profiles, L0(h) where some interesting resemblance to other independent results in the literature are shown.

9909-135, Session PMon1

A single detector stereo-SCIDAR for Mount Stromlo

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Laser ranging measurements and satellite imaging are conducted by the ANU Research School of Astronomy and Astrophysics and EOS (Electro-Optic System) at Mount Stromlo as part of the Space Environment Management Cooperative Research Centre (SEMCRC) to support debris tracking and orbit prediction. Atmospheric turbulence lead to distortions in the measured data. Adaptive optics (AO) systems counteract those distortions and improve the resolution of the laser ranging measurements and satellite imaging systems.

To assist in the design of the Adaptive Optics Systems, we need to gather information on the atmosphere at Mount Stromlo: r0, tau0, and the turbulence Cn^2 profile, so that the turbulence at the mirror and dome, ground layer and the free atmosphere can be distinguished. The SCIntillation Detection And Ranging (SCIDAR) Technique is used to measure Cn^2. With this technique the scintillation of two stars is measured and their autocorrelation function is computed, providing a measurement of the turbulence profile. This technique usually uses one detector on which the two images of the stars are simultaneously recorded. However, the images overlap which leads to a loss of information and hence a reduction of resolution for the different height layers.

The introduction of Stereo-SCIDAR (Shepherd et al 2014) overcomes this issue by separating the two images and applying two separate image sensors. However, this increases the opto-mechanical, the opto-electronic components and the cost. We introduce a new Stereo-SCIDAR system separating the scintillations from the double star, but using only one single detector. This has been shown for a Low Layer SCIDAR (LOLAS) system with extremely wide double stars (200 arcsec). We investigate this technique by detecting the scintillation patterns of double stars with separation from 4 to 30 arcsec, allowing some flexibility in the altitude span and resolution achievable with the system, while retaining a simple optical set-up. We selected a state of the art 2048 x 2048 pixels, high dynamic range sCMOS camera as the beam imager. We show first, preliminary results of this system and investigate its feasibility for further development.

9909-138, Session PMon1

The statistics of atmospheric turbulence at Maunkea measured by RAVEN

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Atmospheric tomography in adaptive-optics (AO) is a technique to reconstruct the 3-dimensional structure of the atmospheric turbulence with measurements from multiple wave-front sensors (WFS) in wide-field AO.

The performance of such systems depends strongly on the accuracy of the tomographic reconstruction. The latter relies on prior statistical knowledge of the turbulence such as layer altitude and strength of turbulence layers. Moreover, the wind speed and direction at each altitude is also required for some advanced algorithms such as predictive control.

These atmospheric parameters can be estimated from measurements of multiple Shack-Hartmann wave-front sensors (SH-WFSs). In addition, the (often short) time-scales on which the frozen-flow assumption is valid can be quantified.

In this paper, we show the statistics of turbulence strength, layer altitudes, outer scale, and wind speeds and directions at Mauna Kea estimated from telemetry of multiple SH-WFSs of RAVEN, an on-sky multi-object AO demonstrator tested at the Subaru telescope. We detail how to use spatial- and temporal-correlations of slopes for parameter estimation. We provide statistics of the temporal evolution and distribution of atmospheric parameters as well as the temporal de-coherence of turbulence based on telemetry acquired in 2014 and 2015.

9909-139, Session PMon1

Segment phasing: comparing diverse wavefront sensors for the characterisation of a high contrast turbulent module

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Future high-contrast imagers on ground-based extremely large telescopes will have to deal with the segmentation of the primary mirrors. Residual phase errors coming from the phase steps at the edges of the segments will have to be minimized in order to each the highest possible wavefront correction and thus the best contrast performance. To study these effects, we have developed the MITHIC high-contrast test bed, which is designed to test various strategies for wavefront sensing, including the Zernike sensor for Extremely accurate measurements of Low-level Differential Aberrations (ZELDA) and COronagraphic Focal-plane wave-Front Estimation for Exoplanet detection (COFFEE). We recently equipped the bench with a new atmospheric turbulence simulation module that offers both static phase patterns representing segmented primary mirrors and continuous phase strips representing atmospheric turbulence filtered by an AO or an XAO system. We characterize the turbulence introduced by the model using different wavefront sensors, and we compare the results. We also show the first results obtained on the bench with the simulator, and we present future prospects that will be explored with MITHIC for segment phasing.

9909-141, Session PMon1

Vibrations in MagAO: resonance sources identification and first approaches for modeling and control

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The 6.5m Magellan Telescope Adaptive Optics System (MagAO), designed by the MagAO Team from the University of Arizona, is noticeable for being the first AO system in the southern hemisphere based on an adaptive secondary mirror, and the first AO system able to provide high quality diffraction-limited images (0.6 to 1.0 microns), reaching resolutions up to 20 [mas].

The system, however, is not exempt from additional factors which are able to reduce the acquired data's reliability. These factors include resonance effect from the telescope itself, as well as the effect of certain instrumentation elements: the primary mirror cell fans, the primary mirror cell glycol cooling pump, and the louvers, among others. It is of great interest to identify these perturbation sources, to be able to recognize precisely how the instrumentation elements are influencing the data captured by the sensors.

This research work has been conducted using closed-loop on-sky data taken during observing runs of the MagAO Team at the Clay Telescope in Las Campanas Observatory, in order to study (under different operation conditions) the frequency-based information taken by sensors of the MagAO system. Data is obtained from both the VisAO science camera and the waveform sensor's modal amplitudes.

For each data acquisition test, the status of the instrumentation elements is registered and normalized Power Spectral Densities (PSDs) from the sensors data are computed. From this data, we are able to observe the main peaks induced by vibration disturbances, and by comparing WFS PSDs (for tests held under different operation conditions), resonance frequencies caused by the system's elements are identified. Additionally, since the PSDs are normalized, the resonance influences can be measured through the calculation of root-integrated-power.

The spectral analysis of the sampled data allows an extension of the research work into obtaining mathematical models to describe the system. For this process, a standard AO loop scheme is used, modelling the system and its inherent resonances, and on the other hand, the effects induced by the instrumentation elements are included as perturbations to the system. Previous work has been made using autoregressive models to obtain a space-state model for the AO loop, evaluating separately the effects of vibrations on each mode (since tip/tilt modes are usually more affected by these effects).

The next step is to improve the system's performance by designing a control scheme for the proposed model. Previous work has been made studying the design of LQG control or frequency-based control for specific AO systems. A predictive control approach (MPC) is proposed, focusing on studying the limitations the AO system may induce for this control alternative, and obtaining comparable results in relation to a LQG approach.

9909-144, Session PMon1

AIR-FLOW: airborne interferometric recombiner, fluctuations of light at optical wavelengths

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The local turbulence is the only part of the seeing degradation that we can actively improve and reduce at the source. It is often a major contribution to the overall seeing and introduces effects that are highly localized and may be difficult to correct. For example, dome seeing is expected to be non-Kolmogorov, with a very small outer scale leading to a preponderance of high spatial frequencies. The first step in controlling the local seeing is to locate and quantify the turbulence present. This requires the development of a new type of sensor, specifically designed to sensitively measure local optical turbulence.

We propose to develop such a sensor, based on a simple Mach-Zender interferometer layout. Two parallel beams traveling through turbulence will incur optical path differences. By measuring the intensity variations in the linear part of the sine wave function of the interferogram, we can extract the variance of the phase and therefore an estimate of the local Fried parameter r0. The instrument is simple in design and can easily be swept though a volume or incorporated into operations, for example to control dome vents. This optical turbulence sensor will be useful to detect local sources of turbulence, which is the first step to improve the image quality due to localized seeing within the dome and the telescope. Eventually it could even be used to optimize the air flow inside the dome by actively controlling dome venting, the implementation of the deflectors or the temperature of telescope components, such as the telescope tube or the secondary mirror spiders.

9909-146, Session PMon1

Turbulence profiling for adaptive optics tomographic reconstructors

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To compensate for random phase fluctuations in the Earth's atmosphere ground-based telescopes employ Adaptive Optics (AO) systems. For high resolution, wide-field astronomy, it is essential that AO systems are capable of tomographically reconstructing the wavefront across a wide scientific field of view. Accounting for the atmospheric turbulence profile is vital for achieving optimal system performance. The accuracy of the turbulence profile can directly impact the AO system performance and these errors are dependent on how the profile is calculated.

Used in conjunction, two wavefront sensors can utilise sufficiently luminous stars to geometrically triangulate the 'seeing' strength as a function of altitude, outlining the heights at which there are layers of considerable turbulence. This can be achieved by external profilers however as there are multiple wavefront sensors within an AO system it is possible to make this measurement internally. Here we show the capabilities of several methods by which the turbulence profile may be calculated from AO telemetry data taken from CANARY, an AO testbed on the 4.2m William Herschel Telescope, La Palma. Simulations, theoretical expectations and on-sky measurements are considered, with the accuracy of the detailed profile outlined at each of these steps.

We then compare profiles determined from this CANARY AO telemetry data to those obtained using two external turbulence profilers, using the SLOpe Detection And Ranging (SLODAR) and SCIntillation Detection And Ranging (SCIDAR) methods. The implications of each approach on the measured profile and tomographic error are presented.

9909-148, Session PMon1

Seeing and turbulence monitor for astronomy

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Optical turbulence characterisation is crucial to understanding site and observational limitations. One widely used instrument for measuring the total integrated seeing is the Differential Image Motion Monitor (DIMM).

We have designed, and successfully tested, a low cost, portable variation on the DIMM design that utilises a low order Shack-Hartmann lenslet array instead of the standard two hole aperture mask, with readily available components. This alternative method gives a better noise estimation, maximises use of the telescope aperture and increases the signal to noise. In addition, the instrument aims to determine limited turbulence altitude information based on scintillation measurements. We will describe the instrument and present measurements from two identical DIMM instruments as well as simultaneous optical turbulence profile data recorded with Stereo-SCIDAR and SLODAR techniques at the Isaac Newton Telescope, La Palma.

9909-149, Session PMon1

Closed-Loop control for tip-tilt compensation on systems under vibrations

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Adaptive optics (AO) is a technology that allows the operation of modern astronomical instruments with high accuracy, mitigating wavefront distortions by reducing the deleterious effects produced by the Earth's atmosphere. This technology has been successfully implemented in almost all modern telescopes. AO has demonstrated to be good mitigating atmospheric distortion, therefore, other sources of aberration have become important, such as mechanical vibrations. This structural vibration can be caused by motors, fans, tracking errors or wind shaking the structure. There have been measurements of vibration in several telescopes, in order to identify and reduce these aberrations. For example, the MACAO system at GEMINI SOUTH presents tip-tilt vibration produced by cryo-coolers.

Various researchers have concentrated on the design of sophisticated control methods for mitigate the vibration using spectral analysis over wavefront sensor measurements of the lower aberration modes, determining frequencies and amplitude of these vibrations. These advanced control methods consists basically in the minimization of a criterion function like LQG control or Predictive Control and Kalman, H-2 and H-infinity optimal control. They demonstrate an improvement in vibration rejection compared with classical control methods.

In this research we show a laboratory demonstration of vibration rejection

of tip-tilt modes using closed-loop control, inducing vibration on the test bench via an eccentric motor with controllable frequency, in order to simulate the structural vibrations mentioned above. We measure the laser vibration and its tip-tilt aberration by checking the spot position when the laser impinges on a camera, and also with a Shack Hartmann Wave Front Sensor. The control action is carried out by a Fast Steering Mirror (FSM) controlled by a Data Acquisition System (DAQ).

Finally, we conclude discussing the technological limitations and possible improvements of the demonstration and its implementation on a telescope.

9909-153, Session PMon1

Vibrations in MagAO: frequency-based analysis of on-sky data, resonance sources identification, and future challenges in vibrations mitigation

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Adaptive optics (AO) is a technology that compensates in real-time optical aberrations caused by atmospheric turbulence. Nowadays most of the large telescopes use this technology, one of these system is MagAO the 6.5m Magellan adaptive optics system. MagAO is the first adaptive secondary mirror based (ASM-based) AO system in the southern hemisphere, providing great diffraction-limited visible (0.6 - 1.0 micron) images down to 20 [mas]. These are the highest resolution filled aperture images ever made by a telescope from the ground or space. Despite these significant advances, other sources of perturbations still degrade the image quality, one of the most relevant are mechanical vibrations. Analysis of tip-tilt on-sky data is necessary in order to recognize the strongest vibrations components. Vibration peaks can be detected, power spectral densities (PSDs) are presented to reveal their presence. The main idea is to obtain information about the source of the vibrations and how this element(s) affect the tip and tilt modal amplitudes.

Instrumentation resonance and windshake noise is prejudicial for the performance of telescopes' adaptive optics systems. Thus, it is useful to analyze how the system's instrumentation is affecting the measured data. For this research, on-sky data taken with the MagAO system on October 31st, 2014 (FWHM of ~0.8 [arcsec], mean wind speed of 22 m.p.h.) at the Clay Telescope in LCO is analyzed and compared with data registered on April 17th, 2014. During this observing run, the system's elements, such as fans and pumps, are activated or deactivated in different configurations, collecting data from both the VisAO science camera and the waveform sensor (WFS). Power spectral densities (PSDs) of recorded data are obtained and influences of the system's elements on sensors' frequency response are identified.

The vibrations should be mitigated thanks to mechanical actions, but is highly desirable to develop new methods for measuring vibration in real time and also incorporate appropriate controllers in the adaptive optics systems in order to compensate this disturbance. Instrumentation-induced resonances, close-loop gain and future challenges in vibrations mitigation techniques are discussed.

9909-156, Session PMon1

The bistatic geometry for Na LGS profiling: results at Teide Observatory

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Here we are presenting the first results of Na Laser Guide Star (LGS) profiling in real time for the ESO-IAC LGS experiment at Teide Observatory (OT). In previous works, we have pointed out the importance of the bistatic configuration for mesosphere Na LGS profiling, while routinely operating in AO systems. The bistatic configuration is one possible solution. The configuration used in the experiment involved the ESO compact and transportable Wendelstein LGS Unit (WLGSU) and a secondary observing telescope (IAC80) with a baseline of 126 m, allowing real time monitoring of the LGS elongation and the relative Na distribution in the profile. Large telescopes might require real-time data of the Na layer as an input for the Wave Front (WF) reconstruction for AO. Therefore, these results are useful for a realistic modeling of the WF sensor (WFS) response working with LGS, especially in ELTs, in which the spot elongation is large. In this work, we also describe the geometry and observing strategies for the bistatic, non sidereal profiling of LGSs.

9909-157, Session PMon1

Simulations on accelerometer-based feedforward vibration suppression in an adaptive optics system for MICADO

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In order to achieve diffraction-limited resolution of the near infrared camera MICADO disturbance effects such as atmospheric turbulences and wind induced vibrations at the telescope mirrors have to be compensated. These effects are compensated by the adaptive optics system using the adaptive mirrors M4 (deformable Mirror) and M5 (Tip-Tilt mirror) of the E-ELT. In MICADO a single conjugated adaptive optics (SCAO) system is used for the first light. Later it will combined with MAORY to an multi conjugated adaptive optics (MCAO) system.

The SCAO system uses the adaptive mirrors of the E-ELT and an additional wavefront sensor.

In the recent years, it was asserted that on large telescopes high frequent vibrations (5 Hz - 50 Hz) disturb the optical path. The common AO proportional integral (PI) controller was not able to completely compensate these vibrations. Hence a model based feedback controller (for example the linear quadratic gaussian controller (LQG)) was developed, which allowed a compensation for high frequency vibrations. However, for faint guide stars there is still a problem. The exposure time of the wavefront sensor is increased in order to achieve a larger signal to noise ratio. The consequence of a larger exposure time is a reduced bandwidth of the AO loop (Nyquist-Shannon sampling theorem). In that special case the feedback controller reaches its limits.

Therefore we developed a vibration suppression concept which is independent of the exposure time and is combined with the AO loop. The vibrations are measured by additional accelerometers at the telescope mirrors.

The vibrations are in particular visible in the tip-tilt Zernike modes. Therefore, the tip-tilt displacement of the telescope mirrors are reconstructed from the accelerometer data. The reconstruction is a challenge because of the small acceleration amplitudes and the sensor noise. The amplitudes are added to the control signal of the AO loop which is sent to the adaptive mirrors.

In order to evaluate the concept an AO end-to-end simulation was created including vibrational effects.

The simulation was verified based on measurements data of the first light camera of the large binocular telescope (LBT). We investigated the influence of vibrations on the strehl ratio of AO systems by using different vibration amplitudes, exposure time and magnitudes. Within these investigations, we discussed the use of an accelerometer-based feedforward vibration suppression system on the strehl ratio for faint guide stars. Subsequently an adaptive optics laboratory system was built to show the influence of a feedforward controller in a real environment. First results indicate that for typical high frequent telescope vibration amplitudes and frequencies, our accelerometer-based feedforward controller can fully compensate for the slow feedback control locking on a faint guide star smaller than 13 mag (R-Band). This operation mode will be of particular importance for extragalactic observations, where bright guide stars are rare.

9909-159, Session PMon1

Measuring vertical profiles of turbulence strength, outer scale, and frozen flow using simultaneous SCIDAR and SLODAR

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Scintillation detection and ranging (SCIDAR) and slope detection and ranging (SLODAR) are triangulation techniques for optical turbulence profiling. Both techniques involve fitting turbulence profiles to spatial covariances - pupil intensity covariances in the case of SCIDAR and wavefront slope covariances for SLODAR. The two techniques have different strengths and weakness. In general SCIDAR offers higher vertical resolution and is better suited than SLODAR to measuring the translational velocity of turbulent layers as a function of altitude. The SLODAR technique can often be applied using wavefront sensor data from an existing adaptive optics (AO) system and is more sensitive to outer scale effects than SCIDAR.

We describe a dual SCIDAR-SLODAR instrument that implements both techniques simultaneously on the 2.5-metre Isaac Newton Telescope on La Palma. We explore how a combined analysis of the data from the two methods can be used to compensate for the techniques' invidivual weaknesses. In particular we consider how non-Taylor flow and the outer scale affect the two techniques and how a combined analysis can help to make better-constrained measurements of these parameters.

9909-163, Session PMon1

Turbulence profiling using the MOAO pathfinder CANARY on-sky data

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CANARY is the Multi-Object Adaptive Optics (MOAO) pathfinder for the future MOAO-assisted integral-field spectrograph proposed for the E-ELT. From 2010, the LESIA and Durham teams have acquired a very large amount of on-sky data, from both Natural and Laser Guide Stars (NGS,LGS) WaveFront Sensor (WFS) measurements.

The DMs are driven using a tomographic reconstruction of the on-axis turbulence based on off-axis measurements, which requires the computation of covariance matrices Cn2(h) and L0(h)- dependant. The turbulence spatial properties must thus be retrieved to perform the turbulence compensation. Moreover, the knowledge of the wind speed profile is also required for LQG command ([Sivo., 2014]) and data analysis.

We propose an overview of these home-made techniques developed to achieve this turbulence characterization based on the Learn & Apply algorithm. Thanks to a model of the WFS measurements spatial covariance, we are able to fit the turbulence and outer scale profiles, as parameters, to get the best matching between this model and the empirical covariance matrix.

About the wind speed, we work on the spatio-temporal cross-correlation of each WFS data and consider, using the Taylor hypothesis, that this cross-covariance map for a given delay can be fitted by a modeled spatial covariance map corresponding to some particular pupil shift. Using this retrieved shift and set temporal delay, we deduce the wind speed and direction.

We finally propose a statistical overview of these relevant parameters of the turbulence based on thousands data sets acquired on-sky using CANARY.

9909-165, Session PMon1

A new method for high fidelity sodium profiling

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The elongation and variability of Laser Guide Stars (LGS) created in the mesosphere are marginally known and not a limiting phenomena for the largest telescopes currently in operation. Nevertheless, across the E-ELT pupil, this elongation takes such proportions that it can significantly impact the quality of the turbulence measurements. Wavefront sensing on Laser guide stars with extreme elongation is a major area of research to overcome a critical technological issue for the commissioning of the E-ELT and the optimization of the scientific return from its instrumentation. A previous analytical and numerical study demonstrated that the impact of these effects could be minimized using dedicated numerical strategies both when processing the WFS data and for wavefront reconstruction. From this study it appears that an accurate knowledge of the Sodium layer profile is required to avoid biased estimates of the WF slopes, whatever the centroiding method.

We propose a new method to estimate the Sodium layer profile from images obtained with a dedicated profiler. This method is similar to image deconvolution and is based on the minimization of a maximum likelihood criterion with respect to the profile function and the position and brightness of possible background stars. In this paper, we first derive an image model as a function of the laser beam function, the turbulent PSF at the focus of the profiler, the Sodium profile and additional background stars modeled as point sources at given positions and with given brightness and express the maximum likelihood criterion from this model based on the noise model in the image. We introduce an appropriate regularization term on the profile to ease minimization and lower the impact of noise and some a priori on stars positions and brightness (from catalogs and / or previous images from the profiler and based on the tracking model). We also discuss implementation related issues and a possible optimization based on the use of GPUs to reach almost real-time performance. We finally discuss the performance of the method, in particular in the context of the elongated LGS experiment that will conducted during phase D of the CANARY project.

9909-168, Session PMon1

Atmospheric turbulence profiling using the SLODAR technique with ARGOS at LBT

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ARGOS is the Ground Layer Adaptive Optics system of the Large Binocular Telescope, it uses three Laser Guide Stars, generated by Rayleigh backscattered light of pulsed lasers. Three Shack-Hartmann WFS measure the wavefront distortion in the Ground Layer.

The SLOpe Detection And Ranging (SLODAR) is a method used to measure the turbulence profiles. Cross correlation of wavefronts gradient from multiple stars is used to estimate the relative strengths of turbulent layers at different altitudes. We present here the results on sky of the SLODAR profile on ARGOS and the results of the wind profile.

9909-169, Session PMon1

The study of variability of the atmospheric turbulence in the region Lake Baykal

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It is known that the angular resolution of ground-based telescopes is limited by the influence of atmospheric turbulence. Increasing its parameter for solar and stellar telescopes is important problem of modern observational astronomy. Presented results allow to choose the levels for multi-mirrors adaptive optical (AO) systems, and to estimate the parameters of the classic AO-system.

The results of astroclimatic conditions research at the Sayan Solar Observatory (SSO) site and at the Baikal Astrophysical Observatory (BAO) site are shown in this article. Vertical distributions of temperature fluctuations are obtained using NCEP/NCAR Reanalysis data as well as atmospheric layers with high turbulisation are identified. To determine the heights of atmospheric layers with high air turbulence for BAO on the archive data of NCEP/NCAR Reanalysis data were estimated vertical profiles of values of dispersion fluctuations in air temperature. Dispersion pulsations of air temperature was estimated for frequencies corresponding to the natural synoptic period (5 – 7 days). We are presented over the period from 1984 to 2014 vertical averaged profiles of the variance of temperature pulsations of air for night and daytime, respectively.

In the daytime the intensity of the pulsations of temperature becomes higher than at night. For comparison we also analyzed vertical profiles of the variance of temperature, are presented too. The variance of temperature pulsations were evaluated according to the archive of NCEP/NCAR Reanalysis data available on each isobaric level at the location of the BAO during the same observation period. At the location of the BAO is the most turbulized layers are also located on the heights of 3 and 12 km altitude location BAO these layers correspond to the altitude of about 2.5 km and 11.5 km.

Evaluation of the Fried parameter from simultaneous optical and meteorological observations pent the period on March 2015 at average air temperature of -9*C. and average wind speed 2.2 m/s. Our data shows the probabilistic likelihood of the frequency of occurrence of values of the structural characteristics of the pulsations of the refractive index held between on March month 2015 at medium temperature. The values of the structural characteristics of the refractive index of air correspond to previously measured winter. The difference of values of meteorological observations over optical due to the location of the weather station in close proximity to the telescope.

The average values of the radius of the atmospheric coherence estimated from methods based on the spectral characteristics of atmospheric turbulence in a wide range of scales – 4.6 cm. Obtained atmospheric coherence is close to the observed or estimated values from other techniques.

A project is financially supported by the Russian Science Foundation grant ?15-19-20013.

9909-171, Session PMon1

A sensitive new instrument for atmospheric turbulence studies

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Using a numerical simulation, a new approach to determine the wave structure function and therefore the astronomical seeing, is presented and discussed. This method is based on the study of the diffraction pattern produced by a double-slit at the focus plane of a telescope. The phase screens are simulated by using the FFT based method and Kolmogorov's law about atmospheric turbulence. From the scattered wave intensity, the wave structure function is calculated by taking into account both phase and amplitude fluctuations.

This means that we can obtain a seeing value which is independent of the propagation distance between the turbulent layers and the ground level (Fresnel diffraction effect).

A mask with a double slit, which size is of the order of few centimeters, allows us to obtain a diffraction pattern in the focus plane of the telescope. Fluctuations in phase and amplitude of the complex field generate fluctuations in the diffracted intensity from which the wave structure function is deduced.

Comparison between the theoretical seeing, used to generate the phase screen, and the retrieved seeing showed the validity of this method. That comparison was done in the usual range of the seeing (0.2 -- 3 arcsec) and the altitude (0--20 km). In bad seeing conditions ($>$ 2 arcsec) we found that this approach over-estimates the seeing but the relative error remains within 10 per cent.

A measurement campaign is being held in order to compare the seeing measured with this approach and that measured by a DIMM.

9909-121, Session PMon2

Imaging exoplanets with TMT: from characterizing young jovians with NFIRAOS/IRIS to imaging rocky planets at 10 microns

Christian Marois, NRC-Dominion Astrophysical Observatory (Canada); Spencer Bialek, Univ. of Victoria (Canada)

The potential for 30m class telescopes is enormous, given the smaller inner working angle and D^4 advantage, opening a vast array of new science capabilities. I will discuss work-in-progress to develop a high-contrast imaging module for NFIRAOS and IRIS to allow first-light detailed characterization of known young gas giant planets. The ExAO coronagraphic system will pioneer a new “super-Nyquist” wavefront AO control scheme to achieve high-SNR detections of planet, even if they are located outside the central “dark hole”. New science capabilities

will include R-5000 J- to K-band spectroscopy with IRIS, the ability of high-SNR time-dependent spectroscopic/photometric analysis, and fiber-fed spectroscopy for the brightest planets to reach "extreme" spectral resolution. The much higher spectral resolution will enable a vast array of new science observations to be performed, including radial velocity to search for large moons, and Doppler imaging.

In addition, I will also review the TMT 10 microns rocky planet science case, and the remarkable potential of an ExAO would have operating at this wavelength. I will present the various challenges involved in designing such an instrument and the various possible solutions that we are planning to test in the coming few years.

9909-124, Session PMon2

A preliminary study for a visible MCAO system at VLT-AOF

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In this paper we present numerical simulations and an initial design for a visible MCAO system for the VLT-UT4 telescope. The proposed concept takes great advantage of the existing HW developed for the Adaptive Optics Facility (AOF) at the VLT-UT4, in particular the 4x20W Toptica lasers and the adaptive secondary mirror with 1170 actuators. The mentioned units makes the VLT-AOF a unique facility to develop a second generation AO system aiming to provide corrected FoV at short wavelength. In particular the flux provided by the four lasers steerable on sky and the high density of actuators (20cm equivalent on M1) provides the temporal bandwidth and the spatial sampling to push the correction down to the visible wavelengths. In addition to this the request of a reasonable size corrected FoV with uniform performance calls for an MCAO system. For such reason here we propose to complement the AOF with post-focal DMs that together with the VLT DSM can provide a corrected FoV of roughly 20/30 arcsec diameter size. An additional challenge for the system is the provided a large sky coverage. Such condition comes from the efficiency of LO wavefront sensors that use field NGS. The presented simulations give some first results for (a) the achieved performance at visible wavelength 0.4-0.9 um as a function of DMs and tip tilt NGSs characteristics (b) the achieved system sky coverage after. Pushing performance toward visible wavelengths calls for embedded and efficient post-processing methods. Being able to capture short-exposure science images (with the trade-off on noise and overheads), would allow retrieving the ultimate performance by compensating the residual turbulence aberrations left over by the AO system. Considerations about advanced analysis tools that may potentially relax the system constraints are discussed. Finally the paper presents a conceptual arrangement for the opto-mechanics of the considered AO module including the additional DMs and wavefront sensors.

9909-126, Session PMon2

SOUL: the single conjugated adaptive optics upgrade for LBT

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We present here SOUL: the Single conjugated adaptive Optics Upgrade for LBT. Currently, there are 4 SCAO systems operating at LBT, all composed by an Adaptive Secondary Mirror (672 actuators) and a Pyramid Wavefront Sensor (30x30 sub-apertures). Two of these SCAO systems feed the interferometric focal stations of LBTI, while the remaining two provide the correction for the two LUCI spectro-imagers. Starting the on-sky operations in 2010, these systems provided the first high contrast images ever on 8m-class telescopes in the NIR. The use of state-of-the art devices is critical for the AO performances and, after about 10 years from the LBT SCAO design, the technological development made significant steps forward, especially in the visible detector field. SOUL will upgrade the two main AO system components: the wavefront sensor and the adaptive secondary. Replacing the current wavefront sensor CCD with an Electron Multiplied CCD, we will provide: a faster read out and framerate (2kHz instead of 1kHz) at lower noise (< 1e- instead of ? 10e-) for better rejection of disturbances, and a higher spatial sampling (40 instead of 30 sub-apertures on the pupil diameter) for improved reduction of aliasing error. The firmware of the adaptive secondary mirror will be upgraded allowing the full AO loop running at 2kHz and dealing with the increased number of sub-apertures.

Here we present the results of the preliminary design study of the SOUL project. This includes the error budget analysis, the design for the implementation of the new WFS camera, the adaptive secondary firmware upgrade and the end-to-end numerical simulations for the performance estimation. The simulations show that the higher spatial sampling and system frame rate allow correcting more modes with a larger control bandwidth, increasing so the Strehl Ratio (SR) in the case of bright guide stars and enabling operations at shorter wavelengths. The gain in magnitude (for a given SR) offered by SOUL is estimated to be around 1.5-2 magnitudes at all wavelengths in almost all the range of reference star brightness (7.5 < mR < 18). The gain in reference star magnitude implies a significant improvement of the sky-coverage that is currently the main limitations of the SCAO systems working with natural guide stars. SOUL will increase the sky coverage of the current systems up to a factor 10 at all wavelengths from R to M.

Upgrading all the 4 SCAO focal stations, SOUL will provide this benefit to the 2 LUCI NIR spectro-imagers, the LBTI interferometer and to the upcoming new generation instruments as the 2 SHARK IR and visible high resolution imagers and the planet-finding spectrometer iLocater. Moreover, it represents the first step toward the visible interferometry as proposed in the Live project.

9909-130, Session PMon2

Using tomographic AO for scintillation compensation in high-precision photometry of exoplanet transits

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As an exoplanet passes in front of its host star it blocks some of the light. This reduction in intensity is observable by telescopes and is used to deduce the presence of a planet orbiting a distant star and a wealth of information about it.

Transit photometry is a powerful technique for extrasolar planet detection and characterisation. By performing time-resolved photometry of exoplanet transits simultaneously in a number of different wavelength bands, it is possible to derive information about the temperature distribution, dynamics and composition of the exoplanet's atmosphere.

The difficulty with such observations is that although the targets are bright, the variation one needs to detect is very small (typically ?1%, ?0.1% and ?0.01% for Jupiter, Neptune and Earth sized planets respectively,

around a sun-like star). Although this is within the capabilities of modern detectors, when the light from the star passes through the Earth's atmosphere regions of turbulence cause intensity fluctuations (seen as twinkling by the naked eye), called scintillation.

Scintillation noise due to the Earth's turbulent atmosphere can be a dominant noise source in high-precision astronomical photometry when observing bright targets from the ground. Accurate knowledge of scintillation noise is important to enable performance assessment, calibration and optimisation of photometric instrumentation. It is also useful when fitting models to photometric data, for example, extrasolar planet eclipse light curves, and to help develop scintillation correction concepts.

Adaptive Optics (AO) is a mature technology which can be used to correct for the blurring of astronomical images by the Earth's atmosphere, however no adaptive technique currently exists for scintillation.

Conjugate Plane Photometry attempts to reduce scintillation noise from a single turbulent layer by a combination of pupil reconjugation and apodisation. This system is non-adaptive and is limited in the situations in which it will perform.

Here we describe an adaptive scintillation correction technique using a tomographic Adaptive Optics system to make a 3D model of the turbulent atmosphere and hence correct the intensity variations caused by all turbulent layers.

This technique, in combination with the large apertures of ground based telescopes, make them an ideal facility for very high-precision photometry, enhancing sensitivity for the detection and characterisation of extrasolar planets. Therefore, AO with scintillation correction could be competitive with the precision of space-based measurements and the larger collecting areas will enable fainter targets to be observed and higher spectral and time resolution photometry.

9909-131, Session PMon2

Utilizing simultaneous pupil plane and focal plane telemetry for exoplanet imaging

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The coming generation of ELTs has the potential to provide unprecedented imaging and spectroscopy of exo-planetary systems, if the difficulties in achieving the extremely high dynamic range required to differentiate the planetary signal from the star can be overcome to a sufficient degree.

Fully utilizing the potential of ELTs for exoplanet imaging will likely require simultaneous and self-consistent determination both the planetary image and the unknown aberrations in multiple planes of the optical system, using statistical inference based on the wavefront sensor and science camera data streams.

It is demonstrated at a theoretical level that simultaneous millisecond telemetry has the potential to surpass current speckle suppression techniques such as ADI, SDI and electric field conjugation methods.

Simulations show that these methods can also effectively reduce the inner working angle, which is a critical parameter for the success of exoplanet searches.

9909-136, Session PMon2

Experimental results on using artificial neural networks for accurate centroiding in Shack-Hartmann wavefront sensors with elongated spots

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The use of adaptive optics in extremely large telescopes brings new challenges, one of which is the treatment of images from Shack–Hartmann wavefront sensors. When using this type of sensor in conjunction with laser guide stars to sample the pupils of telescopes with diameters of more than 30 m, it is necessary to compute the centroid of elongated spots, whose elongation angle and aspect ratio are changing across the telescope pupil. Existing techniques, such as the matched filter, have been considered as the best ways to compute the centroid of elongated spots, but these are not good at coping with the effect of a variation in the sodium profile. In a 2014 MNRAS article, we introduced a new technique for centroiding using artificial neural networks. This technique takes advantage of the neural network's ability to cope with changing conditions and can outperform existing algorithms. We developed comprehensive simulations to explore this technique and compare it with existing methods. For this paper, we implemented a laboratory setup to produce the spot elongation, emulating a changing Sodium profile as well as using a phase screen to generate turbulence. We compared the same techniques as in our original paper, confirming that artificial neural networks are an alternative for accurate centroiding, with similar complexity when compared to matched filter, in terms of computing capacity.

9909-137, Session PMon2

SRAO: the first southern robotic AO system

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The in-development SRAO will be the first Southern Robotic AO system, capable of confirming and characterizing planet candidates produced by major new transit surveys. SRAO is a moderate-order natural guide star AO system with an innovative photon-counting wavefront sensor, allowing guiding on faint stars with the 4.1m SOAR telescope. The system will deliver diffraction-limited imaging in the NIR on targets as faint as mV=16. With the proven robotic AO software developed for Robo-AO, SRAO will be capable of observing overheads on sub-minute scales, allowing at least 200 observations per night. SRAO will attain three times the angular resolution of the Palomar Robo-AO system, and with its NIR camera will attain much higher sensitivity to faint companions. In addition to exoplanet science, SRAO will compliment Robo-AO in a full-sky, stellar neighborhood multiplicity census. SRAO will also perform follow-ups to transient events discovered in large-sky-area surveys, such as stellar merger events and supernovae.

9909-140, Session PMon2

Dynamic modeling and analysis of adaptive optics system for CGST

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Chinese Giant Solar Telescope (CGST) is the next generation infrared and optical solar telescope of China, which is proposed and pushed by the solar astronomy community of China and listed into the National Plans of Major Science and Technology Infrastructures. CGST is currently proposed to be an 8 meter Ring Solar Telescope (RST) with width of 1 meter, the hollow and symmetric structure of such an annular aperture facilitates the thermo control and high precision magnetic field measurement for a solar telescope. RST has collecting area of 22 square meters, which equals to a 5 meter full aperture telescope, but its spatial resolution is 8 meter, thus it can observe the fine structure in near infrared bands as DKIST and EST do in visible bands, therefore it can relieve the stringent requirement of control systems, such as active control and adaptive optics (AO). AO is an indispensable tool of CGST to obtain diffraction limited observations. For RST, how to realize AO involved wavefront sensing and correcting, and the degree of compensating in a narrow ring aperture is the primary problem of AO implementation of CGST. Consequently, we investigate the whole dynamic wavefront reconstruction and control process based on Shack-Hartmann measurement in RST by an end to end modeling. Performances of AO in RST with different geometry of subaperture, measurement noise level and control bandwidth are simulated and analyzed. Error propagation of wavefront reconstruction is paid particular attention to, for there is a potential risk that the error propagation in an annular aperture is larger than that in a full aperture, which probably has the fatal effect on reconstruction precision. The results show that RST can realize diffraction-limited imaging in wavelength of 1 micrometer with the aid of AO system, which meets the demand of most science cases of CGST in near infrared waveband.

9909-142, Session PMon2

Adaptive optics for high-resolution spectroscopy

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So far, High Resolution Spectrographs (HRSs) work in seeing limited-mode, i.e. the size of the slit/fiber projected to the sky is equal to the seeing (order of the arcsec). The linear size of the instruments is directly proportional to the entrance slit, while the cost of the instrument scales like D^2. In addition, his stability and his feasibility are also affected (for the grating element especially). Several paths are explored nowadays to mitigate this issue, that will increase with future ELTs instruments. One of them is to use an Adaptive Optics system to reduce the beam etendue, i.e. the size of such HRSs, without loosing in light collection capacity.

Except few attempts to couple light into single-mode fiber-fed HRSs, AO systems have been used and optimized for high angular resolution and high contrast imaging. The classical way to characterize their efficiency, the so called Strehl Ratio (SR), therefore not the most appropriate figure of merit for an instrument aiming at sensitive spectroscopy on faint targets.

In this work, we focus on the Encircled Energy (EE) to characterize the efficiency and design an AO system feeding an HRSs. We derive global parameters aiming at finding the best compromise between sensitivity and EE. We then present the preliminary design of the foreseen AO injection module of the future spectrograph NIRPS (Near Infra-Red Planet Searcher) for the 3.6m-ESO telescope at La Silla Observatory. The requirements to reach by this module are in one hand defined by the magnitude of the natural guide star, 12 in the I band in order to follow the brightest M-type stars of the TESS satellite candidates. And the other hand by the fact that NIRPS + HARPS can operated simultaneously which limits the wave-front sensor spectral range to the gap between NIRPS and HARPS: 0.7-0.9 micron. According to theses parameters, a deformable mirror of 14x14 actuators and a wave-front sensor Shack-Hartmann (SH) with 14x14 subapertures can reduce the diameter of the EE=50% to 0.3" (FOV) for all the NIRPS spectral domain. The optimal frequency of the control loop depends on the star magnitude, for faint stars (I>10) the system can operate at 250Hz and for bright stars at 500 Hz in order to maximize the EE.

A relatively simple AO module can reduce the size of the entrance slit by a factor 3 with the same collection capacity than a spectrograph working in seeing limited-mode.

9909-143, Session PMon2

Development of a novel three-dimensional deformable mirror with removable influence functions for high precision wavefront correction in adaptive optics system

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Deformable mirror is a widely used wavefront corrector in adaptive optics system, especially in astronomical, image and laser optics. Conventional DM has position-fixed actuators and corrects different aberrations with same actuator arrangement. In this paper, a new structure of DM is proposed, which has removable actuators and can correct different aberrations with different actuator arrangements. Compared to the one-dimensional motion of actuators in conventional DM, the new structure DM's have two more movement dimensions, so it can be named 3D DM. A 3D DM consists of several reflection mirrors, and every mirror has a single actuator and is independent of each other. Beam to be corrected reflected by these DM units in turn, and the aberration can be corrected with every DM units work together. The position of each DM units is changeable, so the system can be equivalent to a DM with removable influence function. Without consideration of the interval distance, more actuators can be achieved in 3D DM than conventional DM in a specific size, making a better correction result. In addition, as actuators' positions are removable, a specific aberration can be corrected more effectively with an appropriate influence function arrangement. Correspondingly, two kinds of actuator arrangement algorithm are proposed to calculate the proper actuator arrangement, which named random disturbance algorithm (RDA) and global arrangement algorithm (GAA). In RDA, each actuator has a small displacement from its original position, and it is restricted to a specific area near the original position. In GAA, actuators can move everywhere freely and influence functions can be at arbitrary position of the cross section of beam. In this paper, correction effects of these two algorithms are analyzed through numerical simulation. And there is also a comparison between the two algorithms and correction of conventional DM. The simulation results show that 3D DM with removable actuators can obviously improve the correction effects compared to conventional DM. As the two arrangement algorithms, actuator placement is more liberal in GAA than RDA, so GAA commonly has a better correction result. However, the algorithm of GAA is more complex and it takes more time to calculate. On the other hand, 3D DM can achieve a specific correction effect with fewer actuators than conventional DM, and significantly reduce the cost. Some other factors that will influence the correction result are also analyzed, such as the diameter of influence function, iterative steps and actuator displacement distance of the algorithm. Different from conventional DM, the diameter of influence function of 3D DM can be designed as any value we want, while that of conventional DM is determined by the coupling coefficient, which is hard to change. There is an appropriate size of influence function diameter for a given beam diameter to achieve the best correction result. A relevant experiment is also carried out to confirm the simulation result.

9909-145, Session PMon2

Development of narrow bandpass etalon for daytime AO observation using laser guide star in mid-infrared wavelength

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(United States)

The use of laser guide star (LGS) in daytime expands the operational time of nighttime-based telescope for AO instruments. The background of this idea is proposed for an instrument for thermal infrared to mid infrared wavelength, because the sky brightness is not so different from night to daytime. The adaptive optics (AO) in thermal and mid infrared wavelength has a great advantage in performance of AO, which can reach almost diffraction limit of even if the extremely large telescope. The sky back ground in 589nm is about a million times brighter than bright night, though, the bandwidth of sodium return light is a few GHz. The narrow bandpass filter at this wavelength makes possible to use LGSs during the day.

We have manufactured prototype of narrow bandpass interference filters from Materion to test whether sodium laser guide star adaptive optics can be used during the day. Although the initial spectral bandwidth of filter just after the fabrication met the specification, which is 0.3nm in FWHM, the width of spectral bandwidth seemed to be degraded. Also the peak transmission was dropped from the initial condition at 70% down to 25 to 30%.

Based on this prototyping experience, we started to investigate the etalon technology to achieve the extreme narrow band filter. It is very challenging to realize both the high throughput at central wavelength and narrow bandwidth less than 0.1nm. Theoretically, we can specify the parameters of etalon, which has high transmission and extreme narrow band transmission, however, the surface quality of high reflective etalon, coating quality of high reflective surface, maximum size of diameter of etalon, integration and testing method, stability in central wavelength, bandwidth and peak transmission have to be confirmed by prototyping. In this paper, prototyping process and results will be presented.

9909-147, Session PMon2

Getting ready for the first on-sky experiment using an elongated sodium laser guide star

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The use of sodium Laser Guide Star (LGS) for Extremely Large Telescope (ELT) Adaptive Optics (AO) is a key concern due to the perspective effect that produces elongated images in the Shack-Hartmann pattern. In order to assess the feasibility of using an elongated sodium beacon at an ELT, an on-sky experiment reproducing the extreme off-axis launch conditions of the European ELT is scheduled for summer 2016. The experiment is made possible by the synergies between the teams of different ESO member states, using the demonstrator CANARY installed on the William Herschel Telescope (WHT), and the ESO transportable 20W CW fiber laser, embedded in the Wendelstein LGS unit (WLGSU). The laser will be launched 40m off-axis from the WHT pupil edge, to reproduce the E-ELT baseline configuration giving an LGS elongation of about 20''.

CANARY has been upgraded with an elongated sodium LGS Wavefront Sensor (WFS), to be able to compare the wavefronts from a Natural Guide Star (NGS) to the one from the superimposed LGS. In addition, a profiler system has been designed for the 2.50m Isaac Newton Telescope, located 426 meters away. It will be used to produce synchronised images of the sodium plume at an increased spatial resolution and at the frame rate of the WFS, so as to be able to measure the spatial and temporal characteristics of the sodium layer and to extract a reference function from it for feeding centroiding algorithms based on correlation-like methods. The WLGSU will provide the LGS and the photometry done on the LGS during the experiment, taken with the in-built photometric receiver. WLGSU will be tailored mostly in the aspect of the control software and local installations.

In order to prepare for this experiment, an error budget is computed to predict the performance of each centroiding algorithm depending on the sodium layer profile. The incidence of different sources of error such as spot undersampling and truncation, cone effect, laser jitter and noise is analysed. Furthermore, the use of reference function is investigated : it can either be obtained with the profile provided by the INT profiler, or retrieved directly from the spots observed on the Shack-Hartmann. In both cases, the question of adequate sampling and how to get reference slopes are the main concerns. In order to evaluate the sources of error in the experiment, the corresponding error budget is derived through end to end simulations using the AO simulation platform COMPASS. We will present the design and the integration tests of the sodium LGS WFS and the simulation results of the wavefront error analysis.

9909-150, Session PMon2

Last results from the 4RUNNER experiment at LBT

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Over the last years the LBT (Large binocular telescope) extreme adaptive optics (ExAO) system has demonstrated very good performances at visible wavelengths. This capability is of paramount importance for the detection of cold giant planets orbiting nearby stars, for which the bulk of the emission is expected at these wavelengths, yet this represents a very challenging task due to the strong effects of the atmospheric turbulence in the visible. In this work we report on the first results obtained by 4RUNNER, the LBT high contrast imager forerunner recently tested on-sky at visible wavelengths. These results demonstrate once more the extremely good performances of the LBT ExAO system at these wavelengths, both in terms of achieved spatial resolution and contrast. To this regard, we used these data to quantitatively assess the contrast enhancement achieved by employing different post-processing techniques like ADI (Angular differential imaging) and PCA (Principal component analysis), after injecting several different synthetic faint sources into them. Our results show that a contrast of 11 mag is easily obtained in the visible. This is an extremely promising result, given the range of working wavelengths considered.

9909-152, Session PMon2

On-sky demonstration of the GMT dispersed fringe phasing sensor prototype on the Magellan Telescope

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The GMT is an aplanatic Gregorian telescope consisting of 7 primary and secondary mirror segments that must be phased to within a fraction of an imaging wavelength to allow the 25.4 meter telescope to reach its diffraction limit. When operating in Laser Tomographic Adaptive Optics (LTAO) mode, on-axis guide stars will not be available for segment phasing. In this mode, the GMT's Acquisition, Guiding, and Wavefront Sensing system (AGWS) will deploy four pickoff probes to acquire natural guide stars in a 6-10 arcmin annular FOV for guiding, active optics, and segment phasing using a dispersed fringe sensor (DFS). The phasing sensor will be able to measure piston phase differences between the seven primary/secondary pairs of up to 50 microns with an accuracy of 50 nm. Recent simulations by Van Dam, et al demonstrate that the highest sky coverage for the dispersed fringe sensor on the GMT can be obtained in the J-band. To test the dispersed fringe sensor design and validate the performance models, SAO has built and commissioned a prototype phasing sensor on the Magellan Clay 6.5 meter telescope. This prototype will use an aperture mask to overlay 6 GMT-size segment gap patterns over the Magellan 6.5 meter primary mirror. The six diffraction patterns created by these subaperture pairs will then be reimaged with a lenslet array and dispersed with a grism. The phasing prototype has two wavelength channels: an I-band channel that uses a Princeton EMCCD and a J-band channel that uses a Ninox 640 InGaAs camera. Each camera can be read at 100 Hz to "freeze" the atmospheric turbulence. A phase difference across the segment gap causes a shear in the fringes. In Fourier space this leads to a displacement of the location of the side lobes. By stacking the Fourier amplitude of multiple frames and measuring the location of the side lobes, we obtain an estimate of the phase difference. An on-board phase shifter has the ability to simulate an arbitrary phase shift within subaperture pairs. The prototype operates both on-axis and 6 arcmin off-axis either with AO on or off in order to replicate as closely as possible the conditions expected on the GMT.

9909-154, Session PMon2

A testing facility at the Asiago Copernico telescope in the framework of the ADaptive Optics National laboratory of INAF: ADONI

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ADONI laboratory has been proposed in 2012 to better coordinate the activities in Adaptive Optics, gathering the INAF know-how in the AO world, to provide a larger momentum in the international collaborations and to realize a structure capable of managing large AO projects. In April 2015 the activity of ADONI has officially started, with the initial participation of three INAF institutes: Arcetri, Padova and Roma Monte Porzio. In the plan concerning the laboratory activity, it is also foreseen to set-up facilities accessible to the Italian and international AO community, with the purpose of facilitating the testing of critical sub-systems or components (which may be part of instruments under construction), or prototypes of innovative concepts which may require on-sky demonstrations.

In this framework, the largest telescope in Italy, located in Asiago, named Copernico and characterized by a primary mirror as large as 182cm, has been selected to be a suitable facility to accomplish this task. In fact, it is a Cassegrain telescope with a design that allows the possibility to redirect the light toward a Coudè focus, by rotating the tertiary mirror. The Copernico telescope requires to be refurbished in order to implement the Coudè optical train (initially foreseen but never implemented and used till today) and the Coudè laboratory may be properly setted-up to host an optical bench installed for specialized instrument set-ups, on which visiting multi-purpose instrumentation will be accommodated and where the testing activities will be conducted.

Possible examples of cost effectiveness of such a facility include, but are not limited to, the very fast implementation of novel concept of wavefront sensing, the comparison of different kinds or concepts of wavefront sensors, the implementation of new techniques in high angular resolution imaging like lucky imaging, speckle interferometry with phase retrieval, the adoption of specialized pupil planes aperture (like the double opening of LBT or the multiple apertures of GMT) and superresolution approaches. Although not primarily intended for such an use, this facility could also carry on experiments in novel kind of low resolution spectrograph using –for instance- volume phase holographic devices. In connection with a working AO system or with a severe pupil stop down it can also be used to experiment on the sky with various different approaches in coronographic devices.

In this paper we describe the opto-mechanical train at the Coudè focal station to be implemented for the laboratory set-up, and we sketch out the foreseen telescope refurbishing activities to implement a multi-purpose testing facility dedicated to AO related projects.

We also point out that such a facility may be used to host a permanent AO demonstrator system, which may serve both as an experimental setup and as a training system for young researchers approaching the AO community, being education and training of young astronomers also between the main tasks and interests of the newly constituted ADONI laboratory.

9909-155, Session PMon2

CHOUGH: implementation and performance of a high-order 4m AO demonstrator

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CHOUGH is a small, fast project to provide an experimental on-sky high-order SCAO capability to the 4.2m WHT telescope. The basic goal has r_0-sized sub-apertures with the aim of achieving high-Strehl ratios (>0.5) in the visible (>640nm). It achieves this by utilizing existing high-performance equipment where possible and this includes the CANARY experiment: CHOUGH is mounted as a breadboard and intercepts the beam within CANARY via a periscope. In doing so, it takes advantage of the mature CANARY infrastructure but adds new AO capabilities. The key instruments that CHOUGH brings to CANARY are an atmospheric dispersion compensator, 32x32 (1000 actuator) MEMS deformable mirror, 31x31 wavefront sensor, and a complementary (narrow-field) imager. Together these are tied together with an optical relay (the backbone) which uses CotS optics where possible and is central to the breadboard. Correspondingly, CANARY provides a 241-actuator DM, tip/tilt mirror, and comprehensive off-sky alignment facilties together with a RTC. In this work, we describe the CHOUGH optical, mechanical, and electronic design from the perspective of the sub-systems: backbone, ADC, KDM, HOWFS, CAWS, and NFSI. We concentrate on these key sub-systems and their individual performance characterization in the laboratory, and then in the context of the integrated instrument. Included are the constraints which led to the optical design, including a discussion of all-metal diamond-machined mirrors. With an on-sky target date of mid-August, we review the integration of CHOUGH into CANARY as an on-sky instrument and associated tasks involved that allow it to operate (in a limited mode) as a standalone bench or integrated with CANARY. The complementary paper in these proceedings (#????) discusses the control strategy and associated algorithm development that can take advantage of CHOUGH.

9909-158, Session PMon2

On the verification of NFIRAOS algorithms and performance on the HeNOS bench

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NFIRAOS will be the first light MCAO system of TMT. HeNOS is a scaled down version of the instrument, which is designed to mimic its behavior. Its purpose is the verification of the performance predicted through simulations and the demonstration of calibration procedures. It implements four LGS with Shack-Hartmann WFS, aligned in a square asterism, and two deformable mirrors, conjugated to the same altitudes as in NFIRAOS. To obtain a comparable actuator spacing we simulate an 8m telescope with a turbulence generated with three phase screens at different altitudes. There is a large number of NGSs in the field of view (FoV) to evaluate the performance and HeNOS is designed in such a way that the expected degradation of the correction over the FoV matches that of the science field of NFIRAOS. Furthermore, it includes a Pyramid Truth WFS which can pick any star in the field, either for high or for low order measurements.

With this setup we run the MCAO correction including LGS effects like spot elongation, tip/tilt uncertainty and sodium layer variations using the algorithms considered to be used in NFIRAOS. The tests give valuable insight into the behavior of the methods and are compared to the predictions from the simulations. This helps gaining confidence in the simulations done for NFIRAOS and the design choices taken with respect to the update of the reconstruction matrix.

Several other methods are tested with HeNOS, which are necessary for the success of NFIRAOS. The identification of the turbulent layers is done with a SLODAR method, tomographic phase diversity identifies the non-common path aberration. Matched filters are used to compute the centroids for the LGS and the Pyramid Truth WFS keeps track of the varying sodium layer. Additionally, the algorithms proposed for PSF reconstruction on NFIRAOS are tested and evaluated.

We discuss the recent advances on the tests and the impact of the results on the control of NFIRAOS.

9909-160, Session PMon2

Distortion calibration unit for ‘imaka

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The aim of the ‘imaka distortion calibration unit is to characterize the geometric optical distortion of the imaging system. It is designed to operate in at night or daytime, and will allow us to measure how the system changes as a function of the conditions, such as the gravity vector, temperature and humidity. Our calibration unit will limit the amount of calibrations that must be taken on sky by allowing us to replicate observing setups and calibrate during the daytime.

The current design utilizes a pinhole mask to directly measure the distortion of the instrument. The design considerations for such a system are complex. We use simulations and a lab experiment to understand how the physical attributes of a given pinhole mask correspond to errors in the measured distortion. The lab experiment consists of a light source, a pinhole mask on a translation stage, and a low-distortion lens. This setup allows us to measure our ability to centroid on pinhole images as well as measure the centroid error due to changes in hole shape and gradients in the light source. We will demonstrate how different dithering patterns of the mask map to different samplings of the optical distortion.

‘imaka's astrometric accuracy is critical to many of its science cases, including measuring the physical quantities of star forming regions in the galactic plane. These clusters have a high stellar density and are extended to radii greater than 5'. ‘imaka will be ideal for studying such regions; the large GLAO corrected field of view enables accurate astrometry on large scales which allows us to select cluster sources based on their common motion.

‘imaka's calibration unit will also be a demonstration of using a pinhole mask to measure and calibrate distortion in an astronomical instrument to the levels needed for 30-meter class telescopes. The relatively coarse plate scale of `imaka translates to an absolute distortion accuracy in the final focal plane similar to that of the 30-meter class instruments such as the TMT/IRIS instrument. We present the design and performance of the ‘imaka calibration unit.

9909-161, Session PMon2

DRAGON-NG: a configurable and capable AO test-bench

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An astronomical adaptive optics test-bench, designed to replicate the conditions of a 4m-class telescope with observatory-like astroclimatology, is presented. Named DRAGON-Next Generation, it is an evolution of CfAI's DRAGON test-bench which utilizes existing components together with an extensive in-house customized mechnical design work. In contrast, DRAGON-NG is constructed primarilyy from commercial off-the-shelf components with minimal customization (approximately a 90:10 ratio). This permits an optical design which is compact and truly modular: all sub-systems interface via a 18mm pupil conjugate. This permits the reconfiguration of sub-systems or the re-design of any one without affecting the other sub-systems. In other words, DRAGON-NG has been designed for operation for the following modes: (high-order) SCAO, (twin-DM) MOAO, and (twin-DM) MCAO. It is capable of open-loop or closed-loop operation, with natural and laser guide-star emulation (the latter including elongation effects), and with a large number of sub-apertures (upto 5000 slopes), at loop rates of upto 200Hz.

Field angles of upto (from a 4m telescope perspective) 2.4 arcmin can pass through the system and three NGS are available at 9 distinct off-axis field angles and one on-axis. Three LGS are also provided and this includes one on-axis, and are emulate a 90km altitude beacon (Na-layer). The design is dioptric and hardware interfaces are exclusively USB or Ethernet which permits long cable runs to a compact realtime control system and control server. The on-sky compatible real-time control software is open-source (C programming language) and permits experimental validation on DRAGON-NG before transfering to an on-sky system, which is a significant risk mitigation. Additional software developments carried out include a centralized supervisor which interfaces with a database to manage data collected. Together this makes DRAGON-NG both easy to use and flexible in configuration, both of which are pragmatic and therefore encourage a wide range of AO research use rather than specializing in one facet of the subject.

9909-164, Session PMon2

Analysis and verification of the error budget for HeNOS: the test bench for NFIRAOS

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At NRC Herzberg we are developing the Herzberg NFIRAOS Optical Simulator (HeNOS), a test bench to support the development of NFIRAOS, the multi-conjugate adaptive optics (MCAO) system for the Thirty Meter Telescope.

On HeNOS, two ALPAO deformable mirrors are conjugated at the ground and at 11 km of altitude. The laser guide stars are generated by an asterism of four laser diodes and their elongation, caused by the thickness of the sodium layer, is simulated by defocusing in steps the ground deformable mirror during the exposure on the wavefront sensor. A single Shack-Hartmann wave front sensor measures the four laser guide stars, each lenslet having a large enough field of view to image the entire asterism. A grid of natural guide stars, created by a laser diode behind a lenslet array, can be used to measure the tip-tilt aberrations and to track the sodium layer's variation by a pyramid truth wavefront sensor. Three rotating phase screens introduce the atmospheric turbulence, conjugated to the ground, between the two deformable mirrors and at high altitude; turbulence "movies" can also be played by the deformable mirrors.

The purpose of our bench is to verify the performance predicted for NFIRAOS and to test algorithms like the tomographic reconstructor, SLODAR and the MCAO PSF reconstruction that will be used on TMT. To use them on HeNOS, we need first to measure its properties and to characterize its performance. Here we present the error budget analysis and verification for the single-conjugate mode, a necessary step to analyze the system behavior before starting MCAO operations.

9909-166, Session PMon2

Prototyping an ELT scale AO loop in the lab with a spatial light modulator and GPUs

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With Extremely Large Telescopes (ELT) under construction, studies on new strategies to control the waveform are becoming critical. To validate them in the laboratory, access to high density deformable mirrors with thousands of actuators is now mandatory. Several technologies are envisioned for ELTs with various actuators geometries and shape. In this paper, we will present an innovative approach to simulate such deformable mirrors using Liquid Crystal On Silicon Spatial Light Modulator (LCOS-SLM). Such devices provide tens of thousands of degrees of freedom and can be driven at framerates up to about 120Hz. To meet this challenge, GPUs appear as a solution of choice, since they natively support efficient DVI output, the standard interface used with SLMs. Additionally, GPUs provide high compute performance that can be leveraged to implement a variety of shaping models at relatively high framerates.

However, to emulate a complete AO loop, such system must be coupled to a high density wavefront sensor (WFS), of which the pixels data must be transferred efficiently to the GPU. We will present a lab demonstrator hosting multiple GPUs and an off-the-shelf FPGA development board on which an efficient GPU aware data transfer scheme has been implemented to provide adequate data transfer rates from the WFS camera to the GPUs. The latter are used to process the WFS pixels data, derive wavefront measurements, reconstruct the wavefront shape and project it to a given deformable mirror geometry simulated on the SLM. We will present the performance achieved for various system dimensioning from 5k and up to 20k actuators systems in the context of the E-ELT first light instruments.

9909-167, Session PMon2

An engineered design of a diffractive mask for high precision astrometry

Kaitlin Dennison, Univ. of Connecticut (United States); S. Mark Ammons, Lawrence Livermore National Lab. (United States)

We present an engineered design for GeMSDiM, a diffractive mask for the Gemini Multi-Conjugate Adaptive Optics System (GeMS). We: (1) used the optics modeling code ZEMAX to simulate the optical performance of the GeMSDim instrument; (2) engineered a CAD model of the instrument using AutoCAD; and (3) performed a high-fidelity Fresnel simulation of the instrument's optical performance using the IDL PROPER simulator.

9909-170, Session PMon2

Status of an extreme adaptive optics testbench using a self referenced Mach Zehnder sensor

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Extreme adaptive optics (XAO) has severe difficulties meeting the high

speed (>1kHz), accuracy and photon efficiency requirements. An innovative High order adaptive optics system using a self-referenced Mach-Zehnder wavefront sensor allows counteracting these limitations. This sensor estimates the wavefront phase by measuring intensity differences between two outputs, with a lambda/4 path length difference, but is limited by its dynamic range. During the past few years, such an XAO system has been studied by our team in the framework of 8-meter class telescopes. In this work, we report on our latest results with the XAO testbed recently installed in our lab, and dedicated to high contrast imaging with 30m-class telescopes (such as the E-ELT or the TMT). A woofer-tweeter architecture is used in order to deliver the required high Strehl ratio (>95%). It consists of a 12x12 deformable mirror and a 512x512 spatial light modulator, characterized using both mono- and polychromatic light. We present our latest simulation and laboratory demonstration results, including components characterization, close loop performance, and sensitivity to calibration errors. This work is carried out in synergy with the validation of fast iterative wavefront reconstruction algorithms, and the optimal treatment of phase ambiguities in order to mitigate the dynamical range limitation of such a wavefront sensor.

9909-27, Session 8

ESO 4LGSF: Integration in the VLT, Commissioning and on-sky results *(Invited Paper)*

Wolfgang K. Hackenberg, Domenico Bonaccini Calia, Jose Antonio Abbad, José Luis Alvarez, Juan Beltran, Bernard Buzzoni, Mauro Comin, Diego Del Valle, Philippe R. Duhoux, Christophe Dupuy, Gerhard Fischer, Fernando Gago Rodriguez, Ronald Guzman, Pierre Haguenauer, Andreas Haimerl, Ronald Holzlöhner, Stefan Huber, Lothar Kern, Arno van Kesteren, Jean Paul Kirchbauer, Harald Kuntschner, Steffan A. Lewis, Jean-Louis Lizon, Pierre-Yves Madec, Stewart McLay, Ivan Munoz, Juan Canos Palacio, Thomas Pfrommer, Jean-Francois Pirard, Dan Popovic, Marco Quattri, Jutta Quentin, Robert Ridings, Miguel Riquelme, European Southern Observatory (Germany)

The Four Laser Guide Star Facility (4LGSF) is part of the ESO Adaptive Optics Facility (AOF), in which one of the VLT unit telescopes, UT4, is transformed in an adaptive telescope - equipped with a deformable secondary mirror, two adaptive optics systems at the Nasmyth foci and four laser guide star modular units, side launched.

In this paper we present the key results of the acceptance tests performed on the 4LGSF in Europe and the on-sky commissioning results, obtained with the Four Laser Guide Star Unit in stand-alone operation.

The emphasis will be on the design choices, the experience cumulated so far with the lasers and other subsystems, the automatic pointing and focusing aided by the Laser Pointing Camera, the integration with the Telescope control system, the on-sky Commissioning process and results.

9909-28, Session 8

Four generations of sodium guide star lasers for adaptive optics in astronomy and space situational awareness

Celine d'Orgeville, The Australian National Univ. (Australia); Gregory J. Fetzer, Arete Associates (United States)

This presentation recalls the history of sodium guide star laser systems used in astronomy and space situational awareness adaptive optics, analysing the impact that sodium laser technology evolution has had on routine telescope operations. While it would not be practical to describe every single sodium guide star laser system developed to date, it is possible to characterize their evolution in broad technology terms. The first generation of sodium lasers used dye laser technology to create the first sodium laser guide stars in Hawaii, California, and Spain in the late 1980's and 1990's. These experimental systems were turned into the first laser guide star facilities to equip medium-to-large diameter adaptive optics telescopes, opening a new era of LGS AO-enabled diffraction-limited imaging from the ground. Although they produced exciting scientific results, these laser guide star facilities were large, power-hungry and messy. In the USA, a second-generation of sodium lasers was developed in the 2000's that used cleaner, yet still large and complex, solid-state laser technology. These are the systems in routine operation at the 8-10m class astronomical telescopes today. Meanwhile in Europe, a third generation of sodium lasers was being developed using inherently compact and efficient fiber laser technology, and resulting in the only commercially available sodium guide star laser system to date. Fiber-based sodium lasers have been deployed at two astronomical telescopes and at least one space debris tracking station last year (2015). Although highly promising, these systems remain significantly expensive and they have yet to demonstrate long-term, high performance in the field. We are proposing to develop a fourth generation of sodium lasers: based on semiconductor technology, these lasers could provide the final solution to the problem of sodium laser guide star adaptive optics for all astronomy and space situational awareness applications.

9909-29, Session 8

Keck II laser guide star AO system and performance with the TOPTICA/MPBC laser

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The Keck II Laser Guide Star (LGS) Adaptive Optics (AO) System was upgraded from a dye laser to a TOPTICA/MPBC Raman-fiber amplifier (RFA) laser in December 2015. The W. M. Keck Observatory (WMKO) has been operating its AO system with an LGS for science since 2004 using a first generation 15 W dye laser. The dye laser was challenging to maintain and operate, requiring significant manpower and infrastructure resources. The advent of new technologies has significantly improved the efficiencies and operability of lasers, which are important qualities for facility class telescopes. In addition, much has been learned from operations at WMKO and other observatories on laser formats which can improve the coupling efficiency of sodium atoms in the mesosphere with lasers. This has led to higher sodium returns, improving the ability of LGS AO to correct for atmospheric turbulence.

Using diode pump lasers, Raman amplification and a well-tuned second harmonic generator, the TOPTICA laser is able to produce a highly stable 589 nm laser beam for power, wavelength, bandwidth and mode quality. The beam's linear polarization and continuous wave formats along with optical back pumping are expected to improve the coupling efficiencies by factors of 10 or more as compared to the dye laser. At the same time, the efficiency and operability of the laser are gained by reducing its input power and cooling requirement, and the manpower to operate and maintain it. The physical architecture of the laser and its smaller footprint reduce the negative impacts of a moving telescope which have plagued previous laser systems. Fibers are used to transport laser light on the telescope without a beam train to minimize the effects of a changing gravity vector. The system architecture allows the laser to be operated

remotely with continuous diagnostics to monitor its health. Unlike the dye laser, the new laser is ideal for time-domain astronomy as it can be started quickly and reaches its stable operational state in minutes versus hours.

The new laser has been implemented with a new Nasmyth sub-platform to house up to three lasers, a safety system to monitor the laser and the beam environment, an optical bench for diagnostics and steering of the beam, motion controllers, and supporting software. The laser and associated subsystems use the recently implemented Center Launch System (CLS) to further reduce the spot size and negative impacts from aniosoplanatism on larger aperture telescopes. The coupling efficiency of the new laser will be examined, based on its relative power, wavelength, optical repumping, polarization, and its alignment to the magnetic field (telescope azimuth and elevation) for the Maunakea site. This should further improve existing sodium models for lasers with this format. We will present the LGS system on the telescope, the on-sky results compared to existing models, the challenges and operations experience of the laser with the CLS, and the overall LGSAO performance using the NIRC2 science camera. We will also examine next steps for the Keck II LGSAO system allowed by the increase in sodium return.

9909-30, Session 8

LGS return flux: report on the Tenerife optimization experiments and comparison with the Toptica laser results at the VLT

Domenico Bonaccini Calia, European Southern Observatory (Germany); Mauro Centrone, INAF - Osservatorio Astronomico di Roma (Italy); Gianluca Lombardi, Gran Telescopio de Canarias, S.A. (Spain); Marcos Reyes Garcia-Talavera, Iciar Montilla Garcia, Instituto de Astrofísica de Canarias (Spain); Ivan M. Guidolin, European Southern Observatory (Germany); Fernando Pedichini, INAF - Osservatorio Astronomico di Roma (Italy); Thomas Pfrommer, Wolfgang K. Hackenberg, Ronald Holzlöhner, Steffan A. Lewis, European Southern Observatory (Germany)

We report on the Laser Guide Star return flux results and laser optimized parameters, obtained during the field observation campaigns at Observatorio de el Teide, Tenerife, using ESO's transportable 20W CW Wendelstein laser guide star unit, based on Raman fiber amplifiers.

We compare the return flux results of Tenerife with those obtained in Paranal with the Toptica lasers on the 4LGSF system.

The Tenerife campaign has involved six missions and has given LGS return flux measurements of unprecedented statistical significance for different seasons of the year.

To find the optimal laser format for the various ALT/AZ pointing directions, we have made scans in laser emitted power, polarization, linewidth, fraction of D2b repumping, frequency of the D2b repumping.

The work, which we report on, has been done in view of optimizing the laser format specifications for the EELT lasers.

9909-31, Session 8

The TIPC pulsed-laser based on sum-frequency-generation of 1319nm and 1064nm infrared lasers: results from laboratory tests of key performance parameters

Angel C. Otarola, Thirty Meter Telescope (United States); Lu Feng, National Astronomical Observatories (China); Yong Bo, Junwei Zuo, Qi Bian, Li Ming, Qinjun Peng, Zuyan Xu, Technical Institute of Physics and Chemistry (China)

The first light Thirty Meter (TMT) Telescope Multi Conjugate Adaptive Optics system NFIRAOS utilizes a six laser guide star (LGS) asterism, and room is available for a future upgrade to eight LGS in the telescope design. Since 2011 TMT has been exploring the potential of using a 589 nm wavelength pulsed laser, based on a quasi-continuous/sum frequency generation design, as an option for the LGS system. The laser pulse parameters include a pulse length in the order of 100 microseconds, and pulse repetition frequency adjustable in the range from 500 Hz to 800 Hz. The design, prototyping and testing of this pulsed-laser is being carried out by the Technical Institute of Physics and Chemistry (TIPC) in Beijing China, with the support of the National Astronomical Observatories of China (NAOC), both institutes sponsored by the Chinese Academy of Sciences (CAS).

In this talk we will summarize the results from laboratory tests of key performance parameters, such as: wavelength stability, power output and power stability, as well as pulse characteristics and laser beam quality, and will compare the test results with the TMT laser requirements. These performance tests are conducted under various environmental and dynamic conditions compatible with those expected during the operations at the TMT site.

9909-32, Session 9

SPHERE on-sky results: final performance, lesson learned, and possible upgrades *(Invited Paper)*

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The objective of the Spectro-Polarimetric High-contrast Exoplanet Research (SPHERE) instrument is to detect extremely faint astronomical sources (i.e. giant extra-solar planets) in the vicinity of bright stars. The detection capabilities of an exoplanet hunter are largely controlled by its adaptive optics (AO) system. Better AO correction provides improved coronagraphic extinction and fewer residual defects. The challenging SPHERE science goals require a very high-order performance AO system to feed a quasi-perfect flat wave front, corrected for atmospheric turbulence and internal defects, to its focal instruments : differential imaging camera, integral field spectrograph, differential imaging polarimeter. The AO system

of the instrument, known as the Sphere AO for eXoplanet Observation (SAXO), is the 'heart' of the instrument, which 'beats' 1200 times per second to provide unprecedented image quality from a large ground-based telescope operating at optical/near-IR (NIR) wavelengths. As such, SPHERE presents tremendous potential for exoplanet discoveries.

In May 2014 SPHERE was installed on the Very Large Telescope in Chile. After six months and four commissioning runs of extensive and comprehensive tests (for robustness, performance, and ease of use), the instrument was made available first for successful science verification observations and now SPHERE is offered, since April 2015, to the ESO astrophysical community for general science programmes.

We present here an overview of the SAXO characteristics, on-sky performances, first astrophysical results, lessons learned during the commissioning and test periods as well as remaining issues.

9909-33, Session 9

Status and performance of the Gemini planet imager adaptive optics system

(Invited Paper)

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The Gemini Planet Imager (GPI) and its natural guide star adaptive optics system have been optimized for high-contrast imaging of bright stars. GPI AO uses a woofer-tweeter setup, with a high-order MEMS deformable mirror and a Fourier modal basis set reconstructing more than 2000 modes. Advances in both hardware and control, such as WFS spatial filtering, vibration suppression with LQG control, and modal gain optimization improve GPI's contrast capabilities relative to previous generation systems. As a result, GPI achieves median H-band contrasts of 7E-5 and 2E-6 at 0.5" in a single unprocessed 60-second exposure and a fully-processed 60-minute sequence, respectively. With more than 150 stars observed as part of the GPIES campaign, we can now analyze the system's real-world performance under a variety of conditions. We detail performance quantified both by AO telemetry and by science data. In particular, we compare parameters such as guide star brightness, loop frequency and gains, and atmospheric coherence time with both single frame contrast and post-processed multiple-frame sequence contrast. Finally, we discuss how these performance analyses have informed recent and planned system updates.

9909-34, Session 9

The SCExAO high contrast imager: transitioning from commissioning to science

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The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system is an instrument optimized for high-contrast imaging and characterization at <5 lambda/D from the host star. Unlike other similar platforms such as GPI and SPHERE, it is constantly evolving in order to incorporate the latest in state-of-the-art technologies. This makes it the ideal testbed for a high-contrast imager for an ELT.

SCExAO achieves high-contrast by first improving on the correction offered by the facility adaptive optics (AO) system. The Extreme AO loop consists of a pyramid wavefront sensor offering diffraction-limited wavefront sensing in the visible on the 8-m class Subaru telescope, combined with a 2000-element deformable mirror which is modified at >3 kHz in order to flatten the wavefront and offer >90% Strehls when fully commissioned. A Lyot based low-order wavefront sensor is used to track small, non-common path and chromatic fluctuations simultaneously in the near-IR in the coronagraphic focal plane in order to ensure sub-milliarcsecond pointing precision and minimal stellar leakage.

The suite of coronagraphs on SCExAO is extensive and includes, the PIAA, PIAACMC, vector vortex, 4 quadrant, 8 octant and shaped pupil versions. The PIAA, PIAACMC and vector vortex with pupil remapping optics are all optimized for small inner working angles at or below 1 lambda/D. These coronagraphs take full advantage of the flat wavefront and are unrivaled on any other ground-based high contrast imager.

For advanced calibration we can close the loop on the ADC in order to reduce residual chromatic dispersion to < 1 mas in the NIR. In addition we commonly utilize an adaptive grid of speckles which are run to calibrate photometry and astrometry. Unlike other systems however, SCExAO creates incoherent speckles which are far superior in stability and robustness compared to their coherent counter parts.

Making use of the discarded visible light are several visible modules including VAMPIRES, FIRST and RHEA. The VAMPIRES instrument offers diffraction-limited imaging capabilities in the visible thanks to the interferometric imaging technique known as aperture masking. Combined with polarimetry VAMPIRES is actively studying the dusty shells around giant stars with unprecedented fidelity and will begin to investigate the dust disks around young stellar objects. RHEA is a high-resolution Echelle-based spectrograph, which will be fed with a single-mode fiber IFU to spatially resolve the convection cells on the surfaces of giant stars and study their dynamics for the first time.

In addition we are currently developing a post-coronagraphic fiber injection unit to feed the light into the IR doppler instrument known as IRD soon to be installed at Subaru Telescope. This will reduce the photon-noise

from the star allowing for a higher signal-to-noise planet spectrum to be extracted.

In this paper we give an overview of SCExAO and outline the current commissioning status of each module. We present results for the AO-loop, pointing control and the coronagraph performance in the laboratory and on-sky. We then go on to demonstrate the preliminary ground-breaking results achieved to date from science operation in regards to imaging disks, faint companions and dust shells around giant stars.

9909-177, Session PTue1

Linear dark field control: simulation for implementation and testing on the UA wavefront control testbed

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This paper presents the early-stage simulation results of linear dark field control (LDFC) as a new approach to maintaining a stable dark region within a stellar coronagraphic PSF. These results represent the first step in the implementation of LDFC in the UA Wavefront Control Lab as a new wavefront sensing and control technique to be tested. In practice, electric field conjugation (EFC) creates a dark region in the image, and LDFC maintains it by using information from the bright speckle field outside of the dark hole. In theory, LDFC is faster, more sensitive, and more robust than using EFC alone to maintain the dark hole. The concept utilizes the linear response of the bright speckle intensity to wavefront variations in the pupil, and therefore has many advantages as a method for stabilizing the dark hole. To make use of this linear relationship, the first step in the implementation and characterization of LDFC is to determine the limits within which the linear response holds. In this paper, the limits of the detector response's linear regime are presented as an initial step toward the deployment of LDFC on the UA Wavefront Control testbed in the coming year.

9909-180, Session PTue1

Natural guide-star processing for wide-field laser-assisted AO systems

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We present the natural guide-star processing for wide-field laser tomography AO systems.

The approach is based on tailoring the spatio-angular approach whereby the wavefront is estimated directly in the pupil plane avoiding a cumbersome explicit layered estimation, to tilt modes on Extremely Large Telescopes.

Taking the case of Harmoni, the European-ELT's visible and near-infrared (0.47 to 2.45 μm) integral field spectrograph we cover the choice of wave-front sensors, the number and field location of guide-stars, the optimised algorithms to beat down angular anisoplanatism and the performance obtained with different temporal controllers under split high-order/low-order tomography or joint tomography. We consider both atmospheric and far greater telescope wind buffeting disturbances. In addition we provide the sky-coverage estimates thus obtained.

9909-183, Session PTue1

Green FLASH: energy efficient real-time control for AO

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Addressing the problem of the unprecedented computing power required to control AO systems coupled to the associated data rate is one of the major challenges identified in the phase A concept studies for the E-ELT instruments. Thus the simplest control law applied to a multi-laser guide stars system such as MAORY or MOSAIC require computing power of up to a TMAC/s (Tera Multiply Accumulate per second)and associated data rates of the order of several hundreds of Gb/s . While current designs of real-time control systems of most AO instruments are based on the use of specialized microprocessors (DSP) and / or reprogrammable logic chips (FPGA), the complexity and scale of future generation systems make the use of these technologies extremely expensive. In addition, due to the saturation of the power evolution of the X86 processors, the use of this technology requires the implementation of substantial structures, with low energy efficiency. Following the recent development of the high-performance computing market, the development of a new solution for AO RTC based on processors such as GPUs to replace DSP cards is an attractive option. This readily available hardware can potentially provide the computing power necessary at a limited cost and with more energy efficiency. Moreover, complete and optimized programming models are available, such as CUDA, OpenCL and OpenMP, and are compatible with traditional mathematical libraries. This is crucial to ensure the development of a scalable, standards-based RTC solution. In order to study this strategy as well as other technology options such as using reprogrammable logic (FPGA), we are starting a large research program, codenamed Green FLASH, gathering the efforts of academic partners (Observatoire de Paris and Durham University) and industrial partners (PLDA company in France and Microgate in Italy), to select and validate new concepts for real-time control for AO on the E-ELT. Over a period of three years (delivery of a prototype scheduled for the end of 2018) and a budget of about 4M€ mostly funded by the European program Horizon 2020, the goal of the Green FLASH project is to implement a full scale RTC prototype instrument for a tomographic system such as MAORY on the E-ELT. We will present the project goals, the roadmap and the results from the first year of prototypes development.

9909-188, Session PTue1

Kaczmarz and Cimmino: iterative and layer-oriented approaches to atmospheric tomography

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Multi Conjugated Adaptive Optics is based upon tomographic reconstruction of the atmospheric turbulence over the line of sight of a telescope, by means of reconstructing turbulence layers through measurements achieved at slightly different directions in the sky. Different approaches have been developed so far, notably the so called layer-oriented one, experienced with success at the VLT through MAD. Later it has been shown that the problem, once posed in terms of solving a set of linear equations describing the turbulence layers with respect to the

observables, can be solved in an iterative manner through a technique first proposed by Kaczmarz in 1937. While it was speculated that the layer-oriented would asymptotically converge to the same solution, we investigated the generalized problem and we found that the layer-oriented is basically a weighted form of an alternative technique for the same kind of problem (finding the solution of a set of linear equations) invented by Cimmino in 1938. We placed the two approaches in the same theoretical framework using the same notation, and we demonstrated the validity of the speculation. The finding can be used to further investigate the differences between the two methods. The first one iteratively forces the solution to achieve a perfect matching in one direction at a time while the second one privileges the results on the various layers. Although this has just a sort of historical perspective it is interesting to note that the second method, the layer-oriented, is better suited for a limited number of iterations. In fact, in its implementation in the sky the number of iterations performed before commands being applied is actually just one. This single-iteration approach would turn out to produce largely non uniform effects in the field of view when using Kaczmarz's method, which, however, has been introduced assuming a large number of iterations to be performed before the commands being applied. The finding can also be used to trace some preliminary conclusions in terms of speed of convergence, further to suggest that several other approaches invented almost a century ago could be of some practical interest.

9909-193, Session PTue1

The control switching adapter: a practical way to ensure bumpless switching between controllers while AO loop is engaged

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In recent years, advanced control methods have gained significant ground in astronomical Adaptive Optics (AO) systems. In particular, the Linear Quadratic Gaussian (LQG) control has been implemented and tested on a full-scale AO system with the CANARY instrument in 2012 [1]. LQG has also been deployed as the default tip & tilt modes controller for SAXO, the Extreme AO system of the SPHERE planet imager [2], and for pointing and focus control on GPI [3]; LQG has also been included as a baseline algorithm for the low-order control loop of NFIRAOS, the first adaptive optics system of the future Thirty Meter Telescope [4].

Real-time implementation of LQG relies on the so-called state-space form, which enables to adjust its parameters by simply loading a different set of matrices in the system's Real Time Computer (RTC). On-line LQG re-tuning is crucial to obtain and maintain high performance and stability over long observation times, since gains need to be adapted at regular intervals to match changes in turbulence conditions and other disturbances (vibrations, windshake). However, switching from one LQG to another (or back and forth from LQG to integrator control) creates transient "bumps" in control trajectories which may have an adverse (if temporary) impact on the AO loop's stability and performance. One way to eliminate these "control bumps" is to exploit the fact that when the controller about to be switched on is implemented in state-state form, its internal state vector can be adjusted to mimic a fictitious scenario where the old and the new controllers would have operated alongside each other and generated the same control trajectory over a short overlapping period of time. This well-known control engineering trick [5] can be adapted to the special case of AO to manage the switch from LQG to (another) LQG, from LQG to integrator and from integrator to LQG.

In this work, we show how to implement this procedure in the special case of a tip and tilt AO control loop, using a "control switching adapter" – an additional piece of AO RTC software which would need to be activated a few milliseconds before the new controller is switched on to compute the appropriate value of its internal state vector. A simulation of controller switching between an integrator and two different LQG controllers settings is presented.

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[3] "On-sky performance during verification and commissioning of the Gemini Planet Imager's adaptive optics system", L. Poyneer & al., SPIE Conference on Astronomical Telescopes and Instrumentation, 2014.

[4] "Kalman Filter Design for Tip/Tilt, Tip/Tilt Anisoplanatism and Vibration Rejection on Extremely Large Telescopes", L. Gilles, H.-F. Raynaud & al., SPIE Conference on Astronomical Telescopes and Instrumentation, 2014.

[5] The Control Handbook, William S. Levine, IEEE Press, 1996.

9909-194, Session PTue1

Dimensioning the MAORY real time computer

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The MAORY system is the Multi-Conjugate Adaptive Optics module for the European Extremely Large Telescope first light.

MAORY should provide high and homogeneous image quality over the MICADO field of view (about 1 arcmin diameter) and still an accettable correction up to the 2.6 arcmin technical Field of View.

The baseline of MAORY is therefore to rely upon the use of multiple Laser Guide Stars (6), multiple Natural Guide Stars (3) and multiple Deformable Mirrors (DM) correction (M4/M5, that are part of the telescope, and 2 post focal DMs).

The Real-Time Control is a key sub-system of MAORY.

It must collect the measurements from various sensing devices and drive the numerous actuators, that can be part of the telescope (like M4 and M5 mirrors) or part of MAORY itself. Many correction loops are forseen with different updates rates.

The main requirements concerning the system dimensioning and real-time performance depend on the sensors and on the actuators interface and on the Real-Time Data Processing.

In this paper we give a preliminar description of the MOARY Real-Time Control system functional requirements derived from the system baseline at the beginning of the instrument Phase B.

9909-197, Session PTue1

Bridging FPGA and GPU technologies for AO real-time control

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Our team has developed a common environment for high performance simulations and real-time control of AO systems based on the use of Graphics Processors Units in the context of the COMPASS project. Such a solution, based on the ability of the real time core in the simulation to provide adequate computing performance, limits the cost of developing AO RTC systems and make them more scalable. A code developed and validated in the context of the simulation may be injected directly into the system and tested on sky. Furthermore, the use of relatively low cost components also offers significant advantages for the system hardware platform. However, the use of GPUs in an AO loop comes with drawbacks: the traditional way of offloading computation from CPU to GPUs, involving multiple copies and and resulting in unacceptable kernel launch overheads, is not well suited in a real time context. This last application requires the implementation of a solution enabling direct memory access (DMA) to the GPU memory from a third party device, bypassing the operating system. This allows this device to communicate directly with the real-time core of the simulation feeding it with the WFS camera pixel stream. We show that DMA between a custom FPGA-based frame-grabber and a computation unit (GPU, FPGA, or Coprocessor such as Xeon-phi) across PCIe allows us to get latencies compatible with what will be needed on ELTs. As a fine-grained synchronisation mechanism is not yet made available by GPU vendors, we propose the use of memory polling to avoid interrupts handling and involvement of a CPU. Network and vision protocols are handled by the FPGA-based Network Interface Card (NIC). We present the results we obtained on a complete AO loop using camera and deformable mirror simulators.

9909-202, Session PTue1

Thirty Meter Telescope narrow-field infrared adaptive optics system (NFIRAOS) real-time controller prototyping results

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Prototyping and benchmarking was performed for the Real-Time Controller (RTC) of the Narrow Field Infrared Adaptive Optics System (NFIRAOS). NFIRAOS utilizes two deformable mirrors (DM) and one tip/tilt stage (TTS) to perform wavefront correction. The RTC receives wavefront information from six Laser Guide Star Shack-Hartmann WaveFront Sensors (LGS WFS) and one high order Natural Guide Star Pyramid WaveFront Sensor (PWFS) and uses this information to determine the commands to send to the wavefront correctors. NFIRAOS is the first light AO system for the Thirty Meter Telescope (TMT).

The prototyping was performed using dual-socket high performance Linux servers with the real-time (PREEMPT_RT) patch and demonstrated the viability of a commercial off-the-self (COTS) hardware approach to large scale AO reconstruction. In particular, a large custom matrix vector multiplication was benchmarked which met the required latency requirements, all major inter-machine communication was verified to be adequate using 10Gb and 40Gb Ethernet, and standard browser-based technologies were used to implement high performance AO displays. The results of this prototyping has enabled a CPU based NFIRAOS RTC design to proceed with confidence that COTS hardware can be used to meet the demanding performance requirements

9909-203, Session PTue1

Comparison of layer compression methods and joint optimization

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In wide-field atmospheric tomography applications of adaptive optics (AO) systems, tomographic solvers cannot always perform phase delay reconstructions on the full number of layers defined in established statistical atmosphere models (mainly due to restrictions on run-time and stability). Hence, a smaller number of reconstruction layers has to be used. In this poster we investigate the crucial question how to choose appropriate reconstruction layer profiles (heights and cn2-weights) with given small numbers of layers, in order to enable tomographic solvers to achieve acceptable small residuals. A special focus is put on two new and promising approaches for automatic generation of such profiles - namely the a-priori compression method optimal grouping and joint optimization, a method for optimizing the profile during solution of the tomography problem without knowing the exact profile.

We will show comparisons of AO simulations for several tomographic solvers running on different reconstruction layer profiles. The simulations are performed for an ELT setting with realistic atmospheric models on the ESO end-to-end AO simulation tool, OCTOPUS.

9909-206, Session PTue1

Novel technology for reducing wavefront image processing latency

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Adaptive optics is a crucial system for the future extremely large telescopes. The instrument real-time control of these planned AO systems offer an interesting computational challenge which cannot easily be solved with current technologies.

Large amounts of work have been done on reducing the overall AO latency. The majority of this work is aimed at reducing the wavefront reconstruction latency by using many-core hardware accelerators such as Xeon Phis and GPUs. These modern hardware solutions have large numbers of cores and high memory bandwidths while having restrictive I/O capability. This lack of I/O inhibits the efficient data processing needed to be performed by these systems. A single camera for an ELT scale adaptive optics system can produce hundreds of millions of pixels per second that need to be processed. Passing all this data though a CPU and into GPUs or Xeon Phis is inefficient.

The Tilera multi-core processor is a novel technology combining a high number of cores and multiple 10 Gbps Ethernet I/O ports. In this paper, we present performance results of using the Tilera Tile GX36 to process pixel data streaming from a wavefront camera. We describe our testing strategy and show that this hardware is a suitable candidate for E-ELT scale AO systems, offering both high performance and very high stability. Finally, we describe how it could be implemented in a real-time control system to reduce the amount of data needing to be transferred to the wavefront reconstruction hardware.

9909-212, Session PTue1

EDiFiSE full-FPGA adaptive optics: first laboratory results using the IACAT (IAC Atmosphere and Telescope) optical ground support equipment

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This paper presents the EDiFiSE Equalized and Diffraction-limited Field Spectograph Experiment full-FPGA AO system and its first laboratory results. EDiFiSE is a prototype Equalized Integral Field Unit (EIFU) Spectrograph for the observation of high-contrast systems in the Willian Herschel Telescope (WHT). Its Adaptive Optics (AO) system comprises two independent parallel full-FPGA control loops, one for tip-tilt and one for higher order aberrations. Xilinx's Virtex-4 and Virtex-5 FPGA's fixed point arithmetic and their interfacing with the rest of AO components and the user have been adequately dealt with, and a very deterministic system with a negligible computational delay has been obtained. The AO system has been recently integrated in laboratory and verified using the IACAT (IAC Atmosphere and Telescope) optical ground support equipment. About 0.25 Strehl ratio is obtained in the visible range for the WHT with a 9 x 9 subpupil configuration, low star magnitude, wind speeds up to 10 m/s and Fried parameter down to 18 cm.

9909-215, Session PTue1

Novel algorithm implementations in DARC: the Durham AO real-time controller

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The Durham AO Real-time Controller has been used on-sky with the CANARY AO demonstrator instrument since 2010. Over this period, many new real-time algorithms have been developed, implemented and demonstrated, leading to performance improvements for CANARY.

Additionally, the computational performance of this real-time system has continued to improve. Here, we provide details about recent updates and changes made to DARC, and the relevance of these updates, including new algorithms, to forthcoming AO systems. We present the computational performance of DARC when used on different hardware platforms, including hardware accelerators, and determine the relevance and potential for ELT scale systems.

Recent updates to DARC have included algorithms to handle elongated laser guide star images, including correlation wavefront sensing, with options to update references during AO loop operation. Additionally, sub-aperture masking options have been developed to increase signal to noise ratio when operating with non-symmetrical wavefront sensor images. The development of end-user tools has progressed with new options for configuration and control of the system. New wavefront sensor camera models and DM models have been integrated with the system, increasing the number of possible hardware configurations available, and a fully open-source AO system is now a reality, including drivers necessary for cameras and DMs.

The computational performance of DARC makes it suitable for ELT scale systems when implemented on suitable hardware. We present tests made on different hardware platforms, along with the strategies taken to optimise DARC for these systems.

9909-217, Session PTue1

Demonstration of the suitability of GPUs for AO real-time control at ELT scales

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The computational demands on the real-time control system to be used for Extremely Large Telescopes will be challenging. Different hardware is available for this task: CPU (computer), FPGA (Field Programmable Gate Array), Graphics Processing Units (GPU) and specialized components like Xeon-Phi. Several different architectures (including hybrids) are being investigated to assess which solution is the best compromise in terms of performance, development time, software maintenance and cost of hardware.

Durham AO Real-time Controller (DARC) is a modular, flexible and configurable CPU-based real-time control system designed with ELT performance in mind. Its modular approach and flexibility allow the simple addition of hardware acceleration, and also facilitates operation with any camera or deformable mirror type.

In this contribution we present an implementation of DARC where the entire data processing pipeline is executed on one or more GPUs. The pixel data from a camera are retrieved by the CPU and copied to GPU. There they are calibrated (with inclusion of several advanced algorithms), then wavefront slopes are calculated and the wavefront is reconstructed with the traditional matrix-vector-multiplication method. Finally the actuator commands are copied back to CPU to be delivered to the Deformable Mirror.

With dummy data on the scale of an ELT instrument, we have demonstrated that the required frame rates for a single DM can be achieved using a small number of current generation GPUs. We have confirmed this result using pixel data from a real camera.

We have addressed the issue of copying data between CPU memory and the GPUs and present a method of minimising the impact on the system latency resulting from this overhead. This is achieved by copying new data to/from GPU in parallel to processing data that has been copied earlier. We also investigated the limitations of this approach.

As well as using the standard centre-of-gravity centroiding, we have implemented several advanced slope estimation algorithms which will be crucial for the on-sky performance of an ELT. These algorithms are computationally intensive but highly parallelizable so there is a significant benefit from implementation on GPU. We show that the impact of these algorithms on system latency can be minimised by implementation on GPU technology, making their use at ELT scales practical.

9909-218, Session PTue1

Model predictive control for laser shaping

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Laser Guide Star (LGS) are widely used in telescopes with mirrors diameter greater than 4 meter, observatories as Gemini, Paranal and Keck, just to mention a few, have developed and apply Adaptive Optics (AO) systems to improve resolution considerably into observations. Due to remarkably results in AO systems, this technology keeps evolving in order to affront new challenges as TMT and E-ELT. This work aim at optimize quality and speed-up calibration of laser beam, so that to increase the availability telescopes.

First stage consists in simulations to validate the lineal model of the system, corresponding to Fresnel Propagation in near field, which is part of iterative phase-retrieval method. This work aim to achieve a determined

propagation shape of laser beam, the closed loop should be capable to counteract the disturbances that cause distortion on the beam path. Then, second stage, should generate an algorithm of closed loop based in Model predictive Control (MPC) and through simulations corroborate a good performance. Finally, third stage considers validation in a laboratory environment in order to analyze the hardware limitations.

Currently, the first and second stage finished successfully, where has verified that MPC is an appropriated method to solver this kind problem with fast dynamics. In order to obtain convincing result the algorithm are tests for different distribution of amplitude to classic super Gaussian shape, also achieved successfully. Other variable considered are: the computing time; error reference of amplitude; and the convergence solution speed. In addition, ratios are used by evaluate performance of algorithm.

The experimental stage is been implemented rigorously on a laboratory bench in order to validate the algorithm of control. If we got successful results, will mean a huge simplification to calibrate LGS due to the closed loop allow a little error to propagation model, thus, the advantage now consisting in not to have a so complex model that require too much computing time. Instead to its allowing to increase a larger number of actuator of DM, meaning, controlling a mirror bigger with improved resolution.

The relevance to continue development AO system generate great impact at telescope due to this technique tip the balance toward the facility the telescopes on surface ground and not in space by its high cost and limited size. The weakness of this work corresponding to not prove the system in a real telescope to test the performance of control over a bigger system with a larger number of actuator and better computing power, this way test the ultimate performance of algorithm.

9909-219, Session PTue1

Control of tip-tilt mirror: a LMI based anti-windup approach

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This paper adresses the application of LMI-based approach for the control of tip-tilt modes. We focused our attention on saturation phenomena which can occur in a strong turbulence context and in the presence of structural vibration of the telescope. This phenomena can degrade the performance or even destabilize the feedback system that is denoted the “windup” effects. We propose an anti-windup two-step approach which guarantees stability and levels of performance. A controller is first designed to work well in the absense of input saturations. Then, it is modified by an anti-windup block which would modify the control signal when saturations are present. The advantages of the proposed approach are shown through numerical experiments.

9909-221, Session PTue1

Location-grouping algorithm based on limited actuators deformable mirror for high precision wavefront aberration correction in adaptive optics system

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The aberration in the center position of wavefront can be corrected well when the deformable mirrors (DM) used in high-resolution adaptive optics system of telescope. However, for the defocus and spherical aberration of telescope, the four corners of the wavefront cannot be corrected well. At two levels of wave front correction based on the LS (least squares) algorithm and the SPGD (stochastic parallel gradient descent) algorithm, the control elements of wave front corrector of deformable mirrors are subdivided into four parts depending the location.

In wavefront sensor adaptive system, there are several frequently-used control methods. The LS algorithm is fast but suffers from low relatively accuracy. And the SPGD algorithm, simulated annealing algorithm, genetic algorithm, have low correction efficiency. To solve this problem, hybrid LS-SPGD algorithm is proposed, which can get correction effect and improve correction efficiency. The mathematical model for the hybrid LS-SPGD algorithm is established, and numerical simulations and spot correction experiments will be conducted. The probable aspects when it is applied to the practice are analyzed specifically. Judging from the results of the correction, the new method can improve correction effect. At the same time, the four corners of the corrected wave front cannot get a good consistency. Especially the defocus and spherical aberration have great influence on the correction of the four corners of wavefront. To solve this problem, the aberration correction procedure can be divided into two steps.

A novel correction method at different levels and regions of deformable mirror is proposed. At first, the wavefront is corrected by the LS-SPGD algorithm. And then the control elements of wave front correctors in four corners are divided, and every four or five DM units in a corner is a group. Then hill-climbing algorithm is used to correct aberration of four corners of the wavefront, and the local root mean square (RMS) of residual wavefront of every corner is considered as a standard to evaluate the effectiveness of the correction. The control elements in each cluster are driven by the different control voltage which is treated as a control variable in correction process.

The novel hybrid algorithm adaptive optics system corrects the distorted wavefront in the sequence from the center parts to the four corners. Aiming at the random aberration, a 49-element AO model based on the method mentioned in this paper is set up, and a group of phase aberration is simulated to research the effect on correct process.

The results reveal that there is a promising prospect for the novel method to be used in corrections of static aberrations, and showed significant advantages in correction of high order aberration. Numerical simulations and spot correction experiments were conducted, and the results indicated this method can get a high efficiency.

9909-222, Session PTue1

Prediction control method to improve the dynamic performance of a close-loop adaptive optics system

Xinyang Li, Qi Luo, Zhao-jun Yan, Institute of Optics and Electronics (China)

The prediction control method can be used to reduce the dynamic performance of an adaptive optics system (AOS) used for correcting the wavefront distortion of atmosphere turbulence. Some researchers have proved this idea but usually in open-loop condition, which predicts the change of wavefront distortion without corrected by deformable mirror (DM). Those open-loop prediction methods often based on the wavefront or sub-aperture gradients of Hartmann-Shack (HS) wavefront sensors. But in practice nearly all AOS are running in close-loop to reduce the nonlinear error of wavefront sensor and DM. It is difficult to predict wavefront distortion in close-loop. In this paper, prediction methods were proposed to improve the dynamic performance of an AOS running with HS and DM in close-loop. In one method, prediction on reconstructed voltages of DM was added to normal close-loop AOS after parallel-integration control calculation. In another method, the prediction process on reconstructed voltages of DM was joined with the reconstruction process and the integration control process. The Recursive Least-Square (RLS) algorithm was used to calculate the wind speed and control parameters of an AOS

based on the voltages of DM. Both methods can be used to practice close-loop AOS with less modification on control algorithm. Calculations were carried out with measured atmosphere turbulence data from a telescope with an AOS to validate the predict method in different atmosphere turbulence condition. There are 127 actuators in the DM of the AOS. The residual wave-front error, the Strehl Ratio of far-field spot, and the power spectrum densities were calculated and compared between an AOS with and without the prediction method. The results show that the dynamic control performances of an AOS will be improved significantly by using both prediction methods, but the second method will be better for more atmosphere conditions.

9909-223, Session PTue1

Spiders: a problem for the DM control?

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All reflecting telescopes need support structures to hold the secondary mirror.

To cope with the weight of the secondary mirror in the planned ELTs, large support structures must be used.

Inadvertently, these support structures will obstruct several wavefront sensor subapertures fully or at least partly.

These effects, also known as spiders, manifest in the WFS measurements as higher measuring inaccuracies or even missing measurements from completely obstructed WFS subapertures.

Subsequently effects of spiders appear as a set of disconnected domains with valid measurements on the wavefront sensor.

This may, if no proper regularization is used, result in separate piston modes in the DM shape on each disconnected domain.

As the piston mode is in the null-space of, e.g., the SH-WFS, those constant shifts may evolve slowly over time and lead to decreasing Strehl ratios.

In order to overcome this problems we will introduce new ways to control the DM shape.

To avoid those piston modes three different methods are implemented and compared.

Method A: The piston in each DM segment is derived using a lower order Wavelet reconstruction using the FEWHA reconstructor. The so calculated piston is applied to a higher order reconstruction on each DM segment obtained with the CuReD (Cumulative Reconstructor with Domain Decomposition).

Method B: The piston is derived, such that he jumps between the segment are minimized using line integrals on the borders of the segments. This is equivalent to the assumption that “nothing” happens under the spider. This method is more stable then assuming zero measurements on the obstructed sensor subapertures and leads thus to higher Strehl Ratios.

Method C: Use a regularization method to derive the piston on each segment, such that the wavefront statistics are fulfilled.

In this talk we focus this methods for a stable DM control using the CuReD and will compare the obtained results with existing algorithms, namely FrIM and FEWHA using all Wavelet Scales. Both methods use statistical regularization to get an optimal reconstruction quality.

Major focus is as well put on real life simulations using the planned E-ELT spider structures and realistic AO-settings. The results presented have been obtained utilizing Octopus, the ESO end-to-end simulation tool and YAO.

9909-22, Session PTue2

On-sky performance using an LQG controller for tip-tilt correction in regular science observation on GeMS

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AO systems aim at detecting and correcting for optical distortions induced by atmospheric turbulences. They are also extremely sensitive to extraneous sources of perturbation such as vibrations, which degrade their performance. The Gemini South telescope has currently 2 main AO systems: the Gemini Multi-Conjugated AO System GeMS and the Gemini Planet Imager GPI. GeMS is operational and regularly used for science observation delivering close to diffraction limit resolution over a large field of view (85x85 arcsec2). Performance limitation due to the use of an integrator for Tip-Tilt control is here explored. In particular, this type of controller does not allow for the mitigation of vibrations with an arbitrary natural frequency. We have thus implemented a Tip-Tilt Linear Quadratic Gaussian (LQG) controller with different underlying perturbation models: (i) a sum of auto-regressive models of order 2 identified from an estimated power spectrum density (s-AR2) of the perturbation (Meimon et al., JOSA A 2010), already tested on CANARY (Sivo et al., Opt. Exp. 2014) and routinely used on SPHERE (Petit et al., SPIE 2014); (ii) cascaded ARMA models of order 2 identified using prediction error minimization (c-PEM) as proposed in (Massioni et al., SPIE 2012, Juvénal et al., AO4ELT4 2015). Both s-AR2 and c-PEM were parameterized to produce tip or tilt state-space models up to order 20 and up to order 30 respectively.

We present in this paper the results obtained on-sky using these LQG controllers and compare their performance to what GeMS is currently delivering using the classic integral controller. We also discuss the parallelized implementation in the real-time computer and give the strategy adopted to commission this controller in regular operation for GeMS.

9909-174, Session PTue2

Speckle lifetime in XAO coronagraphic images: temporal evolution of the SPHERE point spread function

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The major source of noise in high-contrast imaging is the presence of slowly evolving speckles that do not average with time. The temporal stability of the point-spread-function (PSF) is critical to reach a high contrast with extreme adaptive optics (XAO) instruments. Understanding on which timescales the PSF evolves and what are the critical parameters driving the speckle variability allow to design an optimal observing strategy and data reduction technique to calibrate instrumental aberrations and reveal faint astrophysical sources. In this talk, I will analyze the evolution of the PSF of the XAO instrument SPHERE on the VLT, based on on-sky coronagraphic observations from the first year of operations of SPHERE. I retrieve the timescales of the different sources of aberrations. We show that residuals from the atmospheric turbulence induce a fast, partial decorrelation of the PSF over a few seconds, before a transition to a regime with a linear decorrelation with time, at a rate of a few tens parts per million per second. We analyze the spatial dependence of this decorrelation, within the well-corrected radius of the adaptive optics system. We show the impact on the contrast and show that the meridian passage corresponds to the most stable configuration with the smallest PSF decorrelation rate for an instrument such as SPHERE sitting on the Nasmith platform of the VLT.

9909-176, Session PTue2

High contrast imaging of exoplanets on ELTs using a super-Nyquist wavefront control scheme

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One of the key science goals for extremely large telescopes (ELTs) is the detailed characterization of already known directly imaged exoplanets. The typical adaptive optics (AO) Nyquist control region for ELTs is ?0.4 arcseconds, placing many already known directly imaged planets outside the DM control region and not allowing any standard wavefront control scheme to remove speckles that would allow higher SNR images/spectra to be acquired. This can be fixed with super-Nyquist wavefront control (SNWFC), using a sine wave phase plate to allow for wavefront control outside the central DM Nyquist region. We demonstrate that SNWFC is feasible through a simple, deterministic, non-coronagraphic, super-Nyquist speckle nulling technique in the adaptive optics laboratory at the National Research Council of Canada. We also present results in simulation of how SNWFC using the self coherent camera (SCC) can be used for high contrast imaging. This technique could be implemented on future high contrast imaging instruments to improve contrast outside the standard central dark hole for higher SNR characterization of exoplanets.

9909-181, Session PTue2

High-precision wavefront control using multiple wavefront sensors: the SCExAO experience

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The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) instrument, currently under development for the Subaru Telescope, optimally combines state-of-the-art technologies to study exoplanets and stellar environments at the diffraction limit, both in visible and infrared light (0.6 to 2.4 um). The instrument integrates efficiently an ultra-fast visible Pyramid Wavefront Sensor (PyWFS) operating at 3.5 kHz with a latency below 1 ms (3 times faster than any system currently on-sky), a fast speckle nulling loop at 1 kHz, an asymmetric pupil Fourier wavefront sensor (APFWFS) and a Lyot-based low-order wavefront sensor (LLOWFS) at 170 Hz. All these loops use the same 2k-actuator MEMs deformable mirror to perform their correction.

Using all these wavefront sensors at the same time is essential to achieve the best contrast at about 1 lambda/D: the extreme AO loop cleans the wavefront in visible, the APFWFS corrects residual static low-order aberrations in IR, the speckle nulling loop optimizes the contrast by removing quasi-static speckles on one half of the image plane, and the LLOWFS corrects non-common path low-order aberrations behind the coronagraphic masks.

Combining all these loops together with the same correcting device requires a complex real-time architecture, using both CPUs and a bank of GPUs for speed. The PyWFS is considered as the main loop, while the other wavefront control loops are sending it zero-offset commands. This paper will describe how this system was implemented on SCExAO, its advantage and limitations, and how we will soon reach a loop speed of 10 kHz, necessary for SCExAO's operation on TMT.

9909-184, Session PTue2

The path to visible extreme adaptive optics with MagAO

Jared R. Males, Laird M. Close, Katie M. Morzinski, Olivier Guyon, Philip M. Hinz, The Univ. of Arizona (United States)

The next generation extremely large telescopes (ELTs) have the potential to image habitable rocky planets in the visible, if suitably optimized. This will require the development of fast high order ``extreme'' adaptive optics systems for the ELTs. Located near the excellent site of the future GMT, the Magellan AO system (MagAO) is an ideal on-sky testbed for visible high contrast imaging development. Here we will review some highlights of exoplanet imaging with MagAO's VisAO camera. We will then discuss planned upgrades to MagAO. These include improvements in WFS sampling (enabling correction of more modes) and an increase in speed to 2000 Hz, as well as an H2RG detector upgrade for the Clio infrared camera. This NSF funded project, MagAO-2K, will be on-sky in the Fall of 2016 and will significantly improve the performance of MagAO at short wavelengths. Finally, we describe MagAO-X, a visible-wavelength extreme-AO "afterburner" system under development. MagAO-X will deliver Strehl ratios of over 80% in the optical and is optimized for visible light coronagraphy.

9909-185, Session PTue2

High frame-rate detectivity methods with SPHERE ZIMPOL instrument

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The direct imaging of exoplanet is a leading field of astronomy today. Capturing the few photons coming from a planet witnesses for the chemical composition of its atmosphere. The second-generation instrument SPHERE, dedicated to exoplanet imaging of Jovian-like planets, is now in operation on the European Very Large Telescope [VLT]. Such an instrument relies on an extreme adaptive optics (AO) system to compensate for atmospheric turbulence as well as internal system defects with an unprecedented accuracy.

We propose in this paper to develop new detection methods, based on temporal statistics at high framerate, on visible imaging data already acquired with SPHERE instrument. These data, acquired at high framerate, are a unique opportunity to finely understand the physics of coronagraphic image formation in the particular regime where the temporal behavior of Speckle light residual is frozen. The numerical model of image formation is therefore compared to sky data, and a first analysis is proposed.

9909-189, Session PTue2

SCExAO: on-sky performance of the asymmetric pupil Fourier wavefront sensor

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Contrast detection limits for the direct imaging of extrasolar planets from ground based adaptive optics (AO) observations are mostly driven by the presence of residual static and slow-varying aberrations in the optical path that leads to the science instrument, and that are not sensed by the upstream wavefront sensor.

To measure and compensate for this non-common path error, the Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) instrument relies on a technique known as the asymmetric pupil Fourier wavefront sensor (APF-WFS). This technique uses the Fourier analysis of conventional focal images. This phase retrival problem, known to be degenerate can actually be solved quite simply when some asymmetry is introduced in the system. The insertion of a simple asymmetric pupil stop has proven sufficient to achieve this goal. Assuming reasonable upstream AO correction, a typical 30-second close-loop APF-WFS sequence suffices to compensate the non-common path error experienced by SCExAO after each new telescope pointing. APF-WFS is a powerful tool that senses the true wavefront at the level of the science detector, and leads to unbiased wavefront estimates. Although it introduces additional diffraction spikes to the instrument PSF, the asymmetry is mild enough to be considered as negligible for general purpose imaging.

This paper presents the latest status, linearity properties and reports on the on-sky performance of the APF-WFS sensor, as it is currently implemented on SCExAO, to control low-order Zernike modes in a close-loop system, desiged to offset the zero-point of SCExAO's main pyramid-based AO loop. The paper also shows how the sensor can be used to characterize the so-called low-wind effect experienced by SCExAO.

9909-192, Session PTue2

Speckle nulling wavefront control for Palomar and Keck

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The main requirements for high contrast imaging are an adaptive optics system to sharpen the point spread function by removing atmospheric turbulence, a coronagraph to control diffraction, and image post-processing to remove residual "speckles". Speckle-type errors, caused by optical aberrations after the wavefront sensor of the adaptive optics system (and hence invisible to it) are the dominant source of non-common-path aberrations. These are the most serious current barrier to imaging planets and other faint sources, as they are typically tens to thousands of times brighter than these sources of interest.

"Speckle nulling" is a way to remove speckles optically, rather than in post processing. The technique uses the deformable mirror to put "probe" speckles at the same locations in the focal plane as the offending speckles, then changes the phase of the light to modify the interference pattern. By analyzing the interference intensity on the science camera, it is possible to measure the electric field phase of the offending speckles. Knowledge of the electric field phase allows for speckle removal by putting the opposite phase on the deformable mirror, allowing for large improvements in raw contrast.

We present a speckle nulling code that is currently being used on a number of instruments at Palomar and Keck. The code is self-calibrating, requiring no system model or tuned parameters, and thus can be used with a wide variety of different instruments---current implementations range from fast optical imagers to thermal-infrared coronagraphs. It can operate in open loop or closed loop, though closed loop operation presents some additional challenges that we discuss. We present measured contrast curves demonstrating consistent improvements of 5-10 over the controllable area in the focal plane.

The speckle nulling code is written in a modular fashion, which makes it straightforward to port to different systems. It also allows for high-level scripting of wavefront manipulation and calibration routines. We intend to release it to the general public in the near future.

9909-196, Session PTue2

First on-sky closed loop measurement and correction of atmospheric dispersion

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In the field of exoplanetary sciences, high contrast imaging is crucial for the direct detection of, and answering questions about habitability of exoplanets. For the direct imaging of habitable exoplanets, it is important to employ low inner working angle (IWA) coronagraphs, which can image exoplanets close to the PSF. To achieve the full performance of such coronagraphs, it is crucial to correct for atmospheric dispersion to the highest degree, as any leakage will limit the contrast. To achieve the highest contrast with the state-of-the-art coronagraphs in the SCExAO instrument, the spread in the point-spread function due to residual atmospheric dispersion shouldn't be more than 1 mas in the science band. In a traditional approach, atmospheric dispersion is compensated by an atmospheric dispersion compensator (ADC), which is simply based on model which only takes into account the elevation of telescope and hence results in imperfect correction of dispersion. In this paper we present the first on-sky closed-loop measurement and correction of residual

atmospheric dispersion. Exploiting the elongated nature of chromatic speckles, we can precisely measure the presence of atmospheric dispersion and by driving the ADC, we can do real-time correction. With the above approach, in broadband operation (y-H band) we achieved a residual of 4.6 mas from an initial 17.7 mas and as low as 1.2 mas in H-band only after correction, which is close to our science requirement. This work will be valuable in the field of high contrast imaging of habitable exoplanets in the era of the ELTs.

9909-199, Session PTue2

Robust exo-planet detection in multi-spectral multi-temporal data

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The detection of exo-planets in coronographic images is one of the most challenging data processing task for new instruments like SPHERE and GPI. The difficulty is that the planets must be sought in images where the stellar leakage forms speckles which largely dominate the planetary signal. In this context, robust detection methods may be more suitable as they can take into account the imperfect speckle suppression achieved by image processing methods based on image differences (ADI, SDI) or principal component analysis (PCA) for instance. We recently (Denis & Thiébaut, GRETSI 2015) proposed to use Cauchy distributions (rather than Gaussian ones) to achieve robust detection and show that the corresponding Locally Most Powerful test (LMP) can then be computed on large images by means of FFT's. In this contribution, we first show how to generalize the LMP test to multi-spectral and multi-temporal data. The computations involved by the LMP test are carried out in the limit of a negligibly faint planet, thus the nuisance parameters (such as the speckles) only have to be estimated assuming that there are no planets. This makes the proposed method a perfect post-processing detection device which can be applied to the output of various speckle suppression methods. We demonstrate the improved robustness achieved by the generalized method on simulated and real SPHERE data.

9909-200, Session PTue2

Correlated PSF subtraction using an archive

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Current high contrast imaging PSF subtraction algorithms all use some form of a least-squares minimization to find planets hidden below the speckle noise. Generally, a set of reference images is constructed from the target image sequence using Angular and/or Simultaneous Spectral Differential Imaging (ADI, SSDI, respectively). These techniques alone limit the available number of reference images at separations close to the focal plane mask, therefore limiting the performance of the least-squares (i.e., sensitivity to closer-orbiting planets) vs. performance at wider separations. The solution is to use additional reference images over a longer baseline and/or different spectral window from either the same and/or different target. But, this Reference Star Differential Imaging (RSDI) technique has been mostly ineffective in previous high contrast imaging surveys due to the unknown nature of PSF stability across time and wavelength, until now. The now >200 target reference library from the Gemini Planet Imager Exoplanet Survey (GPIES) allows for a detailed characterization of the GPI PSF stability, which we determine is suitable for RSDI GPI PSF subtraction. We present the results of work to optimize PSF subtraction with the GPIES reference library using an adaptation of the least-squares SOSIE algorithm, designed to minimize speckle noise and also maximize planet throughput. We find that using a reference library is more effective on target datasets with less FOV rotation (i.e., where ADI is less effective) and that the optimal number of the most correlated archival reference images to include in our SOSIE algorithm varies with observing conditions in time and wavelength. Our work is also more generally applicable to any current or future high contrast imaging survey instrument, such as WFIRST or a second generation ELT planet finder.

9909-204, Session PTue2

Focal-plane electric field sensing with pupil-plane holograms

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For direct detection and spectral characterization of exoplanets, a coronagraph is used to suppress the star light. Amplitude and phase aberrations in the optical train fill the dark zone of the coronagraph with quasi-static speckles, limiting the achievable contrast. Focal plane electric field sensing, such as phase diversity introduced by a deformable mirror (DM), provides a powerful tool for correcting this residual star light. Phase probes applied sequentially on the DM inject star light with a well-known amplitude and phase into the dark zone and the resulting intensity images are combined to estimate the residual electric field. The DM can then be used to add light with the same amplitude but opposite phase to destructively interfere with this residual star light.

Using a static phase-only pupil-plane element we create holographic copies of the point spread function (PSF), each superimposed with a certain pupil-plane phase probe. We therefore obtain all intensity images simultaneously, while still retaining a central, unaltered science PSF. The electric field sensing method only makes use of the holographic copies, allowing for correction of the residual electric field while retaining the central PSF for uninterrupted science data collection. In this paper we discuss the feasibility of this method through numerical simulations.

9909-208, Session PTue2

Extreme adaptive optics wavefront control towards high-contrast and extra-solar planet imaging with ELTs

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In order to allow the discovery of other Earths, different teams around the world are conceiving a new generation of instruments and telescopes. These new discoveries will rely on high contrast imaging that requires near perfect wavefront so that speckles of starlight, created by subtle aberrations caused by atmospheric turbulence and by the telescope optics, will not create a glare that would obscure the presence of very faint planets. In our presentation we propose real time wavefront control strategies and a WFS concepts to push the performances. Our main goal is the development of adaptive optics (AO) systems to enable ultra-high-contrast astronomical observations to allow such achievements. From the ground, the core of any high contrast instrument is an extreme adaptive optics (ExAO) system correcting both for atmospheric turbulence and for

internal aberrations of the instrument itself. There are currently several high contrast instruments equipped with ExAO under development around the world (Macintosh, 2006 and Beuzit, 2007) on 8 m class telescopes. For E-ELTs. it is extremely difficult, with the current technology, to achieve ExAO on such large telescopes. To address this difficulty, we have dedicated efforts in R&D for demonstrating the feasibility of the required high-order, high-speed wavefront control despite the increase of the number of actuators for the E-ELT. In this context, we present results obtained with a new wavefront sensor concept, based on the Mach-Zehnder wavefront sensor (MZWFS), allowing to achieve better performances and increased robustness to gaps and discontinuities in the telescope pupil. Thanks to a better sensitivity at high spatial frequencies, such WFS favors a clean correction of the starlight halo at small angular separations where the most demanding contrast is required. We present the latest closed loop performances we obtained with the MZWFS by using numerical simulations and the ExAO bench available at CRAL/CNRS.

9909-209, Session PTue2

Precise wavefront control for stellar coronagraphy: possibilities by a common-path extremely unbalanced interferometer

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Direct exoplanet observations in the visible wavelength range using a stellar coronagraph entail a raw (coronagraphic) contrast of 10e10, which requires a ?/10000 rms wavefront control. In communication, we demonstrate a possibility to effectively increase the accuracy of phase control because of the coherent summation within an amplitude imbalanced interferometer. Such an extremely unbalanced interferometer (EUI) is made mechanically stable due to a common-path schematic.

Despite of existing coronagraphs lab demos have already achieved a 10e10 level of the coronagraphic contrast without the proposed technique, the later can still be considered as an alternative to existing solutions, as having several attractive perspectives. The UV spectral range may be one of the featuring EUI applications: in UV range the AO error remains too large. Another potential EUI application seems to be for wavefront correctors with the larger number of active pixels rather than by deformable mirrors: liquid crystals displays (LCDs), digital micromirror device (DMD)... Their general drawbacks are of a lower accuracy compare to the best quality DMs and the raster (gratings of pixel), which causes a strong diffraction- and scattering effects. Principally, the wavefront control error can be reduced in an unbalanced interferometer which mixes into the wavefront a small fraction of itself, where this small fraction is further adjusted in phase by an AO, however the control error here is effectively reduced because the mixing ratio is a small number.

By interference, the amplitude imbalance ratio is set about 1/0.1 between the arms of EUI which explains the abbreviation of a proposed technique having an extreme amplitude imbalance. The EUI schematic has a DM inserted in an interferometer arm or in a loop if interferometer has common-path. EUI is not a nulling interferometer because it does not aim to attenuate the stellar light, for other uses, such as a telescope guiding, and FOV pointing by a nulled star, etc.

Consider a DM pixel performing a ?/500 rms wavefront modulation step (minimum incremental motion which is under control) and that DM is inserted in the interferometer arm with lower amplitude. After the unbalanced interferometer, the wave becomes phase modulated, within a range that can be much smaller than the initial DM modulation, e. g. of about ?/8000 rms. An amplitude error was treated in a manner similar to the phase error and shows the accurate correction.

We start to test the proposed EUI wavefront control technique in a simple experiment with a common-path interferometer scheme. Fresnel reflection and transmission on beamsplitter (or PBS) introduce chromatic phase-amplitude coefficients, which can be effectively compensated by EUI common-path schematic, similar to the common-path achromatic interfero-coronagraph CP-AIC.

An AO control shows an increased accuracy in wavefront control, if an initial wavefront quality before the EUI unit is better than ?/200 rms, then that wavefront quality can be enhanced in more than one order of magnitude. The EUI with DM shows a wide achromaticity towards larger wavelengths. We hope that the EUI method can be a useful addition for future Earth-like planet observations.

9909-214, Session PTue2

SHARK-NIR coronagraphic trade-offs study

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SHARK-NIR is one of the two coronagraphic instruments proposed for the Large Binocular Telescope (LBT), in the framework of the call for second generation instruments, issued in 2014. Together with the SHARK-VIS, it will offer a few observing modes (direct imaging, coronagraphic imaging and coronagraphic low resolution spectroscopy) covering a wide wavelength domain, going from 0.6μm to 1.65μm.

SHARK-NIR has been undergoing the conceptual design review at the end of 2015 and it has been approved to proceed to the final design phase, receiving the green light for successive construction and installation at LBT.

The current design makes it possible to use two pupil planes and one image plane where apodizers, focal plane masks, and Lyot stops can be used to create high-contrast.

We present the results of the trade-offs study of the coronagraphs that we have designed for SHARK-NIR while taking into account the specifications of the LBT aperture, and of the LBT AO system.

The aperture of the LBT is characterized by a smaller central obscuration (11%) than of most telescope apertures, which is good for high-contrast imaging.

The secondary support structure, however, is asymmetric, and it covers a relatively large fraction of the aperture. This is a potential problem for high-contrast imaging, especially since pupil shifts during the observation must be taken into account.

We review the respective advantages and weaknesses of several types of coronagraphs that we have designed for this aperture, and in particular we give an exhaustive description of the shaped pupils, apodized phase plates, apodized pupil Lyot coronagraphs, and apodized vortex coronagraphs.

9909-173, Session PTue3

On-sky results of the TOPTICA guide star laser

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TOPTICA Photonics AG and partner MPB Communications Inc. have completed the first production batch of ten next-generation sodium guide star lasers. The optical concept of this third-generation sodium laser was first demonstrated in technology demonstrators (2009-2011),

followed by a pre-production unit in 2012. A master oscillator signal from a robust linearly-polarized 1178-nm continuous-wave diode laser with stabilized emission frequency and linewidth of 1-2 MHz, is amplified in a polarization-maintaining (PM) Raman fiber amplifier (RFA) pumped by a high-power 1120-nm PM fiber laser. With efficient suppression of stimulated Brillouin scattering, an unprecedented 40 W of narrow-band RFA output is obtained. The RFA output is mode-matched into a resonant frequency-doubling cavity with a free spectral range matching the sodium D2a to D2b separation, allowing simultaneous generation of an additional frequency component (D2b line) to re-pump the sodium atom electronic population from the F=1 hyperfine ground state. Using a direct diode modulation technique, the return flux can be increased without introducing optical wave front distortions or compromising spatial beam overlap. With demonstrated doubling efficiencies >85%, output powers at 589 nm easily exceed the 18+2W design goal. A detuning option allows for measuring and subtracting the Rayleigh scattering background.

A major effort has been dedicated to integrating all optical components into a ruggedized and reliable system design, providing a maximum of convenience for astronomers. With a cooling-water flow of 5 l/min and an overall power consumption of 700 W, the infrastructure demands on site are minimal. Each system is built in a modular way, based on the concept of line-replaceable units (LRU). A comprehensive system software, as well as an intuitive service GUI, allow for remote control and error tracking down to the LRU level. In case of a failure, any LRU can be replaced within less than four hours. With the remote pumping option, the small 80-kg laser head consisting of RFA and second-harmonic generation stage can be separated by up to 27 m from the larger (600 kg) electronics cabinet. This minimizes the effort for integration with existing telescope infrastructures. The end result is a system designed throughout to provide convenient, turn-key operation at the remote and harsh locations of major optical telescopes. By March 2016 and after rigorous testing by the customers, eight TOPTICA lasers (including a prototype system) will be on-sky at four different major telescopes sites worldwide. This allows us to present a comparative survey of return flux and long-term performance results.

9909-178, Session PTue3

Comparison between observation and simulation of sodium LGS return flux with a 20W CW laser on Tenerife

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We report on the comparison of sodium fluorescence models with observations at Observatorio del Teide, Tenerife (28°N), using ESO's transportable 20W CW Wendelstein sodium laser guide star (LGS) system. This campaign has provided return flux measurements of unprecedented detail regarding Alt/Az laser pointing direction, variation of laser power and linewidth, polarization and D2b repumping. With this extensive set of data we can compare the observed flux with numerical simulations using the open source LGSBloch density matrix simulation code. The physical insight validates our simulation tools and enables us to predict/optimize the performance of the various types of lasers in sodium LGS operation.

9909-179, Session PTue3

Polarization switching of sodium guide star laser for brightness enhancement

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The brightness of the sodium laser guide star is one of the key parameters determining the performance of adaptive optics, which allows ground-based large-aperture telescopes to explore the deep Universe. Improving sodium excitation efficiency by optimizing the spectral, temporal and polarization characteristics of the 589 nm laser beam has been a focus of study in the astronomical community. The use of circularly polarized laser was proposed to have brighter guide star utilizing the optical pumping process. However, the benefits of optical pumping are substantially reduced with the presence of geomagnetic field, since the sodium atoms precess along the magnetic field. The precessing atoms are reoriented faster than the time it takes to establish a beneficial distribution. Precession of the angular momentum does not occur when the laser beam is parallel to the magnetic field, but is maximized for the perpendicular case. Unfortunately, large angles are more typical in astronomical observing. Thomas J. Kane et al. proposed to use a laser source pulsed at the Larmor frequency for improving the brightness of sodium LGS. It works because it allows the laser light to interact with the atoms at a fixed point in the precession cycle. Their simulation shows a photon return double that of an optimized cw laser at the same average power for large angles between laser beam and geomagnetic field. But sodium guide star lasers pulsed at this frequency range are not available and technically challenging to develop.

In this paper, we propose a method of "magnetically resonant pumping" with currently available cw laser to overcome the problem induced by the magnetic field. Magnetically resonant pumping is achieved by switching the polarization of the cw guide star laser between left and right circular polarization at a rate of Larmor frequency.

Our simulation is based on the open-source LGSBloch package for Mathematica. Program for the polarization switching is implemented to carry out the calculation. Program for the polarization switching is implemented to carry out the calculation. A piecewise function is used to define the polarization switching as instantaneous square-wave switching. Similar results are expected for square wave switching with nanosecond leading and falling edges. Sine-wave modulation of polarization is also simulated, although the improvement in the return flux is not obvious. Numerical simulation with ESO's laser guide star system at Paranal as example shows that the return flux can be increased when the angle between geomagnetic field and laser beam is larger than 60°, as much as 50% at 90°. The proposal is significant since most astronomical observation is at angle between 60° and 90°, and it only requires a minor modification to the optics after the current installed cw laser.

The influence of laser irradiance, polarization states, angle between laser beam and geomagnetic field, and repumping fraction on return flux and populations dynamics are investigated to understand the mechanism of return flux improvement in the polarization switching method. The practical implementation of the polarization switching method is discussed. Furthermore, the dependence of return flux on the polarization switching frequency is calculated, based on which an alternative method is proposed for remote measurement of magnetic field.

9909-182, Session PTue3

LGS adaptive optics system with long-pulsed sodium laser on Lijiang 1.8 meter telescope 2014-2016 observation campaign

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During 2014~2016, the Laser guide star (LGS) adaptive optics (AO) system observation campaign has been carried out on Lijiang 1.8 meter telescope Yunnan observatory. During the campaign, two generation LGS AO systems have been developed and installed. In 2014, a long-pulsed solid Sodium prototype laser with 20W@400Hz, a beam transfer optical (BTO) system, and a laser launch telescope (LLT) with 300mm diameter were mounted onto the telescope and moved with telescope azimuth journal. At the same time, a 37-elements compact LGS AO system had been mounted on the Bent-Cassegrain focus and got its first light on observing HIP43963 (mV= 8.18mv) and reached Sr=0.27 in J Band after LGS AO compensation. In 2015, the solid Sodium laser has been upgrade to stable 25W@800Hz while D2a plus D2b repumping is used to increase the photon return, and a totally new LGS AO system with 61-elements Deformable Mirror, 9x9 Shark Hartman wavefront sensor, Real Time Controller based on Linux system, two Tip/tilt mirrors with inner closed loop, Multiple-Photomultiplier Tube (MPMT) tracking detector is established and installed on the telescope. And the throughput for the BTO/LLT is improved nearly 20%. The campaign process, the performance of the two LGS AO systems especially the latter one, the characteristics of the BTO/LLT system and the result are present in this paper.

9909-186, Session PTue3

LGS-AO in daytime: experimental results in detecting the LGS with narrow band filters

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The detection of the Laser Guide Stars (LGS) seen against the sky background, is theoretically possible.

It allows daytime LGS-AO for the thermal infrared instruments, potentially more than doubling the observing time availability of thermal infrared instrument on large and extremely large telescopes., e.g. on ELTs. Also for large solar telescopes, LGS-AO in the solar corona opens new research areas in trying to understand e.g. the processes occurring before and during a solar flare.

In this paper we present the experimental results obtained with an extremely elongated LGS in a joint experiment using the 20W CW fiber laser of the ESO Wendelstein Laser Guide Star Unit and the Vacuum Tower Telescope of the Kiepenheuer Institute für Sonnenphysik, located at Izaña, Tenerife, Canary islands. The VTT is equipped with the 30 milli-Angstrøm tunable filter Hellride.

9909-190, Session PTue3

Back to the optical: a new dawn for LGS AO at shorter wavelengths

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Laser tomography AO (LTAO) is the accepted technology for providing wavefront correction on ELTs at infrared wavelengths, but scientific demand is never static. There are many ELT science cases which require high-sky-coverage wavefront correction at optical wavelengths and this represents the new frontier for AO. Pushing towards shorter wavelengths requires substantial increases in the correction frequency and the modal order of AO, but neither of these present a fundamental limitation to optical-wavelength correction. Instead it is the deficiencies of the tomography itself which come to the fore as wavefront correction at shorter wavelengths is persued. The main limitation for LTAO is that it requires a model for the vertical structure of C_n^2, and this model must be updated to keep up with the changes in the vertical structure of the atmosphere, which are now known to be rapid and substantial.

We argue that the high wavefront accuracy required at optical wavelengths means that the rate at which the model must be updated becomes impracticable and an alternative strategy is required. We propose instead the use of projected pupil plane patterns (P^4) to directly measure wavefront distortions without requiring a model for the vertical structure. We describe how advances in detector technology mean that problems with fluorescence in the monostatic laser launch required with this method can now be straightforwardly overcome, and describe progress towards a future optical-wavelength capability for ELTs. We describe how extra Ps may be added to P^4 techniques to improve its power, up to P^n.

9909-191, Session PTue3

Laser traffic control system upgrades for Maunakea

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The Maunakea Laser Traffic Control System (LTCS) has been in use since 2002 providing a mechanism to prevent the laser guide star or Rayleigh scatter from a laser propagated from one telescope from interfering with science observations at any of the other telescopes that share the mountain. The LTCS has also been adopted at several other astronomical sites around the world to address that same need. In 2014 the stakeholders

on Maunakea began the process of improving LTCS capability to support common observing techniques with enhanced First On Target (FoT) equity. The planned improvements include support for non-sidereal observing, laser checkout at zenith, dynamic field of view size, dithering, collision calculations even when a facility is not laser impacted, multiple alert severity levels, and software refactoring. The design of these improvements was completed in early 2015, and implementation is expected to be completed in 2016. This paper describes the Maunakea LTCS collaboration and the design of these planned improvements.

9909-195, Session PTue3

Laser beam shaping simulations for generation of artificial stars constellations

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Laser guide stars (LGS) technology significantly enlarge the portion of the sky covered by adaptive optics (AO) on optical telescopes, having a large impact on astrophysical and science capabilities in the world's largest observatories. Furthermore all the future visible or near-infrared ground-based telescopes are being designed to use some kind of LGS AO system. Because AO correction is typically limited to a relatively small field of view around a single guidestar, artificial light patterns with multiple reference sources, known as LGS asterisms, are being used. With more than one reference source, it is possible to have more accurate observations (astrometry), better observations in deep space and high-resolution observations over large fields, among others. Despite all the benefits, high power and quality lasers and projection optics are required, increasing the complexity of the LGS AO systems.

Nowadays, the generation of the LGS asterisms is usually carried out with sophisticated layouts by using beam splitters and mirrors or multiple laser sources. The concept of a beam shaping system with deformable mirrors and its potential benefit for laser-based astronomical AO has been recently proposed.

In this work we report the study and analysis of different methods to generate arbitrary patterns of LGS asterisms starting from a single laser beam and optically processes by continuous face-sheet deformable mirrors. The potential benefits of beam shaping for generation of artificial constellations are based on the actual and expected progress in the development of better deformable mirrors along with improvements in laser technology. Some of these potential benefits are: to enhance the quality of the LGS beacons, to precompensate atmospheric turbulence effects, to reduce the number of elements in the beam transfer optics and to minimize the alignment and calibration time before observations. We carried out detailed numerical simulations of optical propagation with novel beam shaping algorithms applied to the generation of astronomical LGS asterisms. The possibility of using multiple DMs to accomplish this task and the differences between near-field and far-field beam shaping algorithms are presented. Parameters like the diameter of the launch telescope, the number of actuators of the DMs and the influence function of the actuators are also evaluated.

9909-198, Session PTue3

Laser pointing camera: a valuable tool for the LGS-AO operations

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In this poster we describe the design, functionalities and full commissioning performance of the Laser Pointing Camera, developed for the ESO Adaptive Optics Facility.

The LPC allows having a fast pointing of the multiple LGS on the AO WFS during the initial acquisition phase of the telescope preset, thus reducing considerably the overheads currently experienced in most LGS-AO systems in operation. By recognizing the field stars as well as the multiple LGS, LPC is insensitive to flexures of the laser launch telescope or of the receiver telescope opto-mechanics.

Moreover, LPC gives regularly the photometry and fwhm of the LGS, as well as the scattering of the uplink beams at the height of 10-15km, thus monitoring the presence and evolution of cirrus clouds.

We will present the Commissioning results of the Laser Pointing Camera, obtained at the ESO VLT during the full 4LGSF Commissioning, and will discuss its possible extension for the ELT operations.

9909-201, Session PTue3

Closed-loop control for laser beam shaping system before guide star projection

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Despite the significant advances in laser guide star for astronomy, the laser beam system usually requires constant and complex system alignments in order to achieve a satisfactory performance in terms of power and quality. During operations, efforts to adjust the laser system can cost an important part of the observation time, even some of the laser systems have been available less than 50% of the time.

The scintillation arises when the phase aberrations induced by turbulence are converted in amplitude fluctuations in the target (receiver, satellite or sodium layer). In the case of laser guide stars formed in the atmosphere, this scintillation not only reduces the energy density applied at the desired point, can also extend the spread to the point that cannot be resolved with sufficient resolution due to the low SNR in the subaperture of the wavefront sensors. The performance of laser projection systems can be improved compensating the effects of scintillation caused by aberrations in the laser source or misalignment in the transfer optics before the laser beam propagating through the aperture.

In case of laser beam shaping, the goal is to maximize the available energy in the focused spot. One of the first approaches to reach phase and amplitude correction simultaneously was proposed by Roggermann and Lee. This configuration has two deformable mirrors, using a phase retrieval method process amplitude and phase measurements to determine the deformation to be applied to each deformable mirror. Systems with two DMs have been intensively used during the past three decades in military and space communications. In case of astronomical field challenges, optical field conjugation has been proposed for applications such as high-contrast detection of planets but without significant efforts regarding laser beam shaping.

Regarding laser system for astronomical AO, laser beam shaping using 2 DMs have been presented for only phase correction where the second mirror is conjugated to the first in order to increase the stroke of overall system and spatial frequency of the correction. Another project use DMs for laser beam shaping but again is focused in only phase correction before laser guide star projection. More recently a novel 2-DM concept for amplitude and phase correction based on phase retrieval techniques was presented by Bechet et al. including a laboratory validation for this method. The studies of both amplitude and phase correction before guide star projection is still new in AO for astronomy.

In this project, we aim to improve the 2-DM concept for amplitude and phase correction through a closed loop configuration using the Linear Quadratic Regulator (LQR). In Sect. 2 LQR and feedback controller design are detailed. In Sect. 3 simulation, numerical results and comparisons are presented. Finally in Sect. 4 conclusions and future work are discussed.

9909-205, Session PTue3

Daylight operation of a sodium laser guide star

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We report contrast measurements of a sodium resonance guide star against the daylight sky when observed through a tuned magneto-optical filter (MOF). The MOF includes an interference filter with 2.88 nm equivalent width and a sodium vapor cell in a magnetic field between crossed polarizers.

The filter has a very narrow transmission profile of approximately 0.008 nm. Our observations were made with the 1.5 m Kuiper telescope on Mt. Bigelow, AZ, which has a separately mounted guide star laser projecting a circularly polarized single-frequency beam of approximately 3.5 W at 589.16 nm. Both the beam projector and the 1.5 m telescope were pointed at zenith; the baseline between them is approximately 5 m. Contrast measurements of the resonance beacon were made on the morning of 2015 November 3 using an imaging camera focused on the beacon and looking through the full aperture of the telescope. The guide star had a V magnitude of 9.8, and we estimate the unfiltered V-band sky surface brightness at 07:15 local time (14:15 UTC) to be magnitude 4.2 per square arcsecond. Assuming a solid angle of 2x2 arcsecond, typical for the field of view of the subapertures of a Shack-Hartmann wave-front sensor, we show that the beacon contrast is improved from 0.17, when looking through the interference filter alone, to 10.0 with the MOF. We interpret our results in terms of the performance of adaptive optics systems for astronomy, with particular emphasis on the thermal infrared wavebands at the coming generation of extremely large telescopes.

9909-207, Session PTue3

Vapor-cell based sodium laser guide star mechanism study lab-bench

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Sodium laser guide star (SLGS) is the key for the success of modern adaptive optics (AO) supported large ground based telescopes, however, for many field applications, SLGS's brightness is still a limited factor. Large amounts of theoretical efforts have been paid to optimize SLGS exciting parameters, that is, to fully discover potential of harsh environment surrounding mesospheric extreme thin sodium atoms under resonant excitation, whether quantum or Monte Carlo based. But till to now, only limited proposals are demonstrated with on-sky test due to the high cost and engineering complexities. To bridge the gap between theoretical modeling and on-sky test, we built a magnetic field controllable sodium cell based lab-bench, which includes a small scale sum-frequency single mode 589nm laser, with added amplitude, polarization, and phase modulators. We could perform quantitative resonant fluorescence study under single, multi-frequency, side-band optical re-pumping exciting with different polarization, also we could perform optical field modulation to study Larmor precession which is considered as one of devils of SLGS, and we have the ability to generate beams contain orbital angular moment. Our preliminary sodium cell based optical re-pumping experiments have shown excellent consistence with Bloch equation predicted results, other experimental results will also be presented in the report, and these results will give a direct support that sodium cell based lab-bench study could help a SLGS scientists a lot before their on-sky test.

9909-210, Session PTue3

Sodium vapor cell laser guide star experiments for continuous wave model validation

Felipe Pedreros Bustos, Johannes Gutenberg Univ. Mainz (Germany); Ronald Holzlöhner, European Southern Observatory (Germany); Dmitry Budker, Johannes Gutenberg Univ. Mainz (Germany); Steffan A. Lewis, European Southern Observatory (Germany)

Recent numerical simulations and experiments on sodium Laser Guide Star (LGS) have shown that a continuous wave (CW) laser with circular polarization and D2b re-pumping should maximize the fluorescent photon return flux to the wavefront sensor for adaptive optics applications. The orientation and strength of the geomagnetic field in the sodium layer also play an important role affecting the LGS return flux. Field measurements of the LGS return flux show agreement with the CW LGS model, however, fluctuations in the sodium column abundance and geomagnetic field intensity, as well as atmospheric turbulence, induce experimental uncertainties and errors.

We describe a laboratory experiment to measure the photon return flux from a sodium vapor cell illuminated with a 589 nm CW laser beam, designed to approximately emulate a LGS under controlled conditions. Return flux measurements are carried out adjusting polarization, power density, re-pumping with about 12% of the power in the D2b at 1713 MHz offset, laser linewidth, and magnetic field intensity and orientation. Comparison with the numerical CW simulation package Atomic Density Matrix are presented and discussed.

9909-213, Session PTue3

The progress of TMT Laser Guide Star Facility

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The Laser Guide Star Facility (LGSF) is one of the first light AO systems of TMT. Its design, manufacturing, testing and integration work is managed and carried out by the Institute of Optics and Electronics (IOE) in Chengdu (China). The LGSF uses multiple sodium lasers to generate and project several LGS asterisms from a laser launch telescope located behind the TMT secondary mirror. The LGSF includes 3 main sub-systems: (1) the laser system, (2) the beam transfer optics and laser launch telescope (BTO/LLT) system, (3) the associated laser safety system. In particular, the BTO/LLT system consists of two components: one is the beam transfer optical path, which includes conventional (mirror-based) beam transfer optics system; the other is the LGSF Top End. The latter includes the Diagnostic system, the Asterism Generator (AG), the Laser Launch Telescope Assembly (LTA) and the Laser Guide Star Acquisition System.

At present, the LGSF is at the preliminary design phase. During this phase, the laser launch telescope trade study, Beam transfer optical path trade study are compared carefully, and some critical components prototypes have been carried out to verify the requirements, such as the polarization status control along the BTO analysis and test, the Fast Steer Mirror (FSM)

prototype test. Finally the optical performance, the displacement budget are discussed in the paper.

The optical performance is mainly related with the laser system, the BTO and LLT. Here, the LLT design is focused on, which is a pivotal subsystem in the LGSF. It is a reflective off-axis structure with a clear aperture diameter of 0.4 m. The design of first mirror is paraboloid and the second mirror is hyperboloid. The LTA Field of View (FoV) shall be circular with a 510arcsec radius without vignetting and shall be focused at an adjustable range between 85 and 235 km. The tolerance analysis of the LTA has been done and the detailed structure has been designed to meet the requirement.

Displacement budget is about the error budgets for the beam centering and pointing errors of the LGSF. The alignment of the LGSF laser beams is defined in terms of (1) the apparent position error of the laser guide star as measured on the NFIRAOS wavefront sensor, and (2) the beam centering error on the laser launch telescope primary mirror and as many other surfaces as we care to monitor (which could be all of them), (3) the active mirrors which are used to compensate the displacement. And then, all these displacements can be divided into contributions from (i) internal misalignments of the LGSF optics and (ii) misalignment of the TMT structure itself. Each of these could be broken down further into flexure, thermal, vibration ..... The displacement budget will be discussed well in the paper.

9909-216, Session PTue3

Development of vertical external cavity surface emitting lasers (VECSELs) for use as monochromatic and polychromatic sodium guidestars

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To date, three types of laser sources have been used to excite mesospheric sodium atoms to use as a sodium guidestar for adaptive optics (AO). All these sources have inherent challenges and a possible fourth source is to utilize a frequency-doubled Vertical External Cavity Surface Emitting Laser (VECSEL). A design for 1178 nm VECSEL to be frequency doubled to be utilized as a sodium guidestar at 589 nm is presented. An 1141 nm VECSEL device is shown to provide a suitable source for simultaneous two wavelength excitation of sodium to provide a polychromatic guidestar. Such VECSELs are shown to present output efficiency above 20% with power in excess of 20 W. Modeling is also presented to validate the efficacy of developing VECSEL guidestar systems for use with current guidestar systems or as a stand-alone guidestar. The model agrees with the data collected with the 3.5 m telescope and narrowband laser guidestar at Starfire Optical Range.

9909-35, Session 10

Review of solar adaptive optics *(Invited Paper)*

Dirk Schmidt, National Solar Observatory (United States)

Adaptive optics is essential for ground-based high-resolution observations of the Sun in the visible wavelength regime. Classical solar AO (CAO) - first introduced at sub-meter class telescopes - is well established for about 15 years. CAO is the enabling technology of the current 1.5-meter class telescopes, and even more for the upcoming 4-meter solar telescopes. MCAO is highly interessting for observations of large active solar regions, and being developed at various institutes.

The latest trend of solar AO development is dedicating systems for observations off the solar limb, using very weak prominences for wavefront sensing.

We will summarize solar AO techniques, current developments and difficulties being encountered.

9909-36, Session 10

Status of the DKIST system for solar adaptive optics

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When the Daniel K. Inouye Solar Telescope (DKIST) achieves first light in 2019, it will deliver the highest spatial resolution images of the solar atmosphere ever recorded. Additionally, the DKIST will observe the Sun with unprecedented polarimetric sensitivity and spectral resolution, spurring a leap forward in our understanding of the physical processes occurring on the Sun.

The DKIST wavefront correction system will provide active alignment control and jitter compensation for all six of the DKIST science instruments. Five of the instruments will also be fed by a conventional adaptive optics (AO) system, which corrects for high frequency jitter and atmospheric wavefront disturbances. The adaptive optics system is built around an extended-source correlating Shack-Hartmann wavefront sensor, a PI fast tip-tilt mirror (FTTM) and a Xinetics 1600-actuator deformable mirror (DM), both of which are controlled by an FPGA-based real-time system running at 1975 Hz. It is designed to achieve on-axis Strehl of 0.3 at 500 nm in median seeing ($r0 = 7$ cm) and Strehl of 0.6 at 630 nm in excellent seeing ($r0 = 20$ cm).

The DKIST wavefront correction team has completed the design phase and is well into the fabrication phase. The FTTM and DM have both been delivered to the DKIST laboratory in Boulder, CO. The real-time controller has been completed and is able to read out the camera and deliver commands to the DM with a total latency of approximately 620 microseconds. All optics and optomechanics, including many high-precision custom optics, mounts, and stages, are completed or nearing the end of the fabrication process and will soon undergo rigorous factory acceptance testing.

Before installing the wavefront correction system at the telescope, it will be assembled as a testbed in the laboratory. In the lab, performance tests beginning with component-level testing and continuing to full-system testing will ensure that the wavefront correction system meets all performance requirements. Further work in the lab will focus on fine-tuning our alignment and calibration procedures so that installation and alignment on the summit will proceed as efficiently as possible.

9909-37, Session 10

Adaptive Optics Facility: control strategy and first on-sky results of the acquisition sequence

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Adaptive Optics Facility is an ESO project aiming at converting Yepun, one of the four 8m telescopes in Paranal, into an adaptive telescope. This is done by replacing the current conventional secondary mirror of Yepun by a Deformable Secondary Mirror (DSM) and attaching four Laser Guide Star (LGS) Units to its centerpiece. In the meantime, two Adaptive Optics (AO) modules have been developed incorporating each four LGS WaveFront Sensors (WFS) and one tip-tilt sensor used to control the DSM at 1 kHz frame rate. The four LGS Units and one AO module (GRAAL) have already been assembled on Yepun.

Besides the technological challenge itself, one critical area of AOF is the AO control strategy and its link with the telescope control, including Active Optics used to shape M1. Another challenge is the request to minimize the overhead due to AOF during the acquisition phase of the observation.

This paper presents the control strategy of AOF. The current control of the telescope is first recalled, and then the way the AO control makes the link with the Active Optics is detailed. Lab results are used to illustrate the expected performance. Finally, the overall AOF acquisition sequence is presented as well as first results obtained on sky with GRAAL.

9909-38, Session 10

On-sky MOAO performance evaluation of RAVEN

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This paper presents the AO performance we got on-sky with RAVEN, a Multi-Object Adaptive Optics (MOAO) technical and science demonstrator installed and tested at the Subaru telescope. RAVEN performs astronomic tomography with four guide stars and provides MOAO corrections simultaneously to the two independent science targets. RAVEN also supports ground-layer AO correction and single-conjugate AO correction. We have successfully completed on May and August 2014 and June 2015 both the engineering and science observations.

We now report Strehl-ratio, Ensquared-Energy, full width at half maximum, and wave-front error from science images on Subaru's IRCS and wave-front sensors telemetry taken during all on-sky observations. We show these metrics as function of different AO modes, atmospheric conditions, guide-star configurations and magnitudes and discuss dependencies of AO performance of RAVEN on these environments. We discuss how our results can be scaled to ELT-sized MOAO systems.

9909-39, Session 10

AO corrected satellite imaging from Mount Stromlo

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Space situational awareness (SSA) is a rapidly growing field for optical telescopes. The goal of SSA is to track as many orbiting objects as possible, both active satellites and debris. These tracked objects are accumulated into a precise catalogue which contains up to date and highly accurate data needed to predict any possible conjuncture. Active satellites can be warned to perform debris avoidance manoeuvres, and possible collisions between debris objects determined in advance.

Orbiting objects need to be precisely tracked and categorised in order to have good orbital data and conjuncture assessment. The most precise way to determine an orbit in low Earth orbit is optically with satellite laser ranging (SLR). SLR operates by propagating a laser pulse from the ground to the target, and collecting returned photons. A precise range can be calculated by timing the laser pulse. Cooperative targets (those with retroreflectors) and uncooperative targets (those without retroreflectors) can be tracked in this manner, with higher power lasers required for tracking uncooperative targets. We plan to improve SLR by adding an adaptive optic (AO) system to compensate for atmospheric turbulence which spreads the laser beam on-sky (ref last SPIE).

Information on the size and shape of the object is also important for orbit propagation. This information when combined with the precise orbit determined with SLR the orbit prediction can reach unprecedented accuracy. We present the development and first results of a satellite imaging AO system for small (1-2m) telescopes. We focused on making a compact and high performance system using modern high stroke deformable mirror (DM) and low noise high rate EMCCD cameras for imaging and wavefront sensing. We are able to track satellites down to magnitude 10 with a Strehl in excess of 20% in median seeing.

We use the satellite as a natural guide star (NGS) on a Shack-Hartmann wavefront sensor with a closed loop rate of 2 kHz. Our system meets the performance requirement of 20% Strehl at a nominal orbiting altitude of 1000 km, but will also operate on objects down to 600 km. Below this altitude the telescope slew rate is so great that even at 2 kHz the AO system does not have the bandwidth to provide enough correction. We have developed a system for processing imaging data in real time to remove the need for derogating optics and large stroke tip-tilt correction.

We have demonstrated this AO system on a 1 m SLR telescope at Mount Stromlo Observatory in Canberra, Australia. We present the demonstration results here and plans to further develop the system for a 1.8 m telescope also located in Mount Stromlo. This next AO system will also be capable of providing orbital information out to geosynchronous orbit using high precision astrometry.

9909-40, Session 11

Development of the near-infrared eAPD array SAPHIRA achieving sub-electron read noise at millisecond full-frame readout *(Invited Paper)*

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In 2007 ESO started a program at SELEX to develop near infrared detectors for wavefront sensing and fringe tracking. The growth technology was liquid phase epitaxy. The arrays required deep cooling to 40K to get acceptable cosmetic performance at high APD gain. The second step was to develop a specific multiplexer tailored to the application of the GRAVITY wavefront sensors and the fringe tracker. The pixel format is 320x256 pixels. The array has 32 parallel video outputs which are arranged in such a way that the full multiplex advantage is available also for small subwindows. Nondestructive readout schemes with subpixel sampling are possible. This reduces the readout noise at high APD gain well below the subelectron level at frame rates of 1 KHz. The third step was the change of the growth technology from liquid phase epitaxy to metal organic vapour phase epitaxy (MOVPE). This growth technology allows the band

structure and doping to be controlled on a 0.1μm scale and to apply solid state engineering techniques. Heterostructures can be designed with the bandgap varying across the diode structure. This generation HgCdTe eAPD arrays has matured and offers an unmatched combination of sub-electron read noise and millisecond full-frame readout at operating temperatures of T=85K. These arrays are sensitive in H and K-band.

First on-sky results have been obtained with the SAPHIRA array at the Palomar Robo-AO adaptive optics system and further applications are planned at the SUBARU and KECKII telescopes. The SAPHIRA arrays have also been deployed in the wavefront sensors and in the fringe tracker of the VLTI instrument GRAVITY. First results with the four auxiliary telescopes of the VLTI have demonstrated stabilized fringes at magnitudes >8 in K-band, which is a major improvement in comparison to previous fringe trackers based on conventional NIR arrays. The SAPHIRA array is also an ideal device for pyramid wavefront sensors. With subelectron readout noise the spatial sampling of the wavefront can be optimized for faint targets. The fast frame rates match the needs of extreme adaptive optics.

With a high temperature anneal it was possible to increases the diffusion length from 2 μm to 30 μm. Due to the long diffusion length the ?c=2.5 μm the HgCdTe absorber layer can be directly grown on a CdTe substrate without a wide bandgap HgCdTe buffer layer using a "pauseless growth" technique. This allows a smooth transition from CdTe to HgCdTe. Due to the large diffusion length the absorber layer can be made thicker. With the removal of the wide bandgap buffer layer limiting the sensitive range to H band on the short wavelength side, the devices now show flat response from 0.8 to 2.5 um. Results obtained with this new diode structure called Mark14 will be presented. In a further development step the CdTe substrate can be removed by a chemical etch to obtain eAPD arrays with panchromatic response. These arrays could also be operated at the wavelength of 598 nm and used for laser guide stars.

For AO systems of extremely large telescopes larger formats are needed. Therefore, a 1Kx1K SAPHIRA array is planned which has 64 outputs operating at 20 Mpixel/s. This corresponds to frame rates of 1.2 kframes/s for a full 1Kx1K single frame readout. The development will be carried out in two steps. First, a 1Kx1K ROIC with a pixel pitch of 12 ?m will be designed and manufactured. A 512x512 pixel eAPD array with the current pixel pitch of 24 ?m will then be hybridized to this ROIC connecting pixels only to every second row and column of the ROIC. This yields a 512x512 pixel array with 24 ?m pixel pitch. In parallel the mesa structure of the HgCdTe eAPD layers for the smaller pixel pitch of 12 ?m will be developed to extend the format to 1024x1024 pixels without the need of developing new ROIC.

9909-41, Session 11

C-RED one: ultra high speed wavefront sensing in the infrared made possible

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While in the visible Electron multiplying CCDs (EMCCDs) improved imaging techniques and permitted a leap especially in life science imaging, no important breakthrough has been made in the infrared imagery since the hybridization of III-V or II-VI semiconductors with low bandgap on CMOS read-out circuitry (ROICs). The EMCCD technology permitted wide readout bandwidths while maintaining ultra low readout noise. For instance the OCAM2 camera has to now the fastest readout speed combined with the lowest readout noise at the same time: it exhibits a readout rate in excess of 132 Mpixels/s while maintaining a readout noise down to 0.1 electron (Feautrier et al. 2010). No equivalent imagers to EMCCDs with embedded carrier amplification were existing up to now in the infrared, neither for short wave imaging (SWIR), nor for mid wave or long wave imaging (MWIR & LWIR).

During the last few years, HgCdTe avalanche photodiodes (APDs) have been demonstrated to be one of the most promising path to build focal plane arrays (FPA) for Infrared low flux and high speed applications such as active and hyper spectral imaging. Several groups (Beck 2001,2004,2006, Kinch 2004, Vaidyanathan 2004, Hall 2005, Reine 2006,2007, Perrais 2007, Rothman 2007) have reported multiplication gains of 100-1000 for low values of reverse bias, around 10V, associated with a quasi-deterministic multiplication yielding a close to conserved signal to noise ratio (SNR) by measuring an excess noise factor F from 1 to 1.2.

First light imaging has decided to make this technology available to everybody with its C-Red one camera which is the first camera ever using an e-APD infrared array. Based on a 320x256, 2.5 ?m cutoff HgCdTe e-APD array deeply cooled to 80K with a high reliability pulse tube cryocooler (MTBF ~ 90 000 hrs), the camera can exhibit a huge readout speed of ~2000 fps full frame while having a readout noise below one electron, thanks to the APD gain in the range of 1 to 60. These unprecedented performances will open a new era for infrared imagery. In addition to the outstanding performances of the detector, First Light Imaging provides a fully integrated system that can be used in demanding environments and requires only an electric power supply and water cooling. No liquid nitrogen or vacuum pumping is needed for the camera operation allowing the continuous use of the camera in a remote environment without any human operator and allowing also a full remote control of the system.

The main application of such a camera is wavefront sensing and we will show solutions to make them and compare its performance with various wavefront sensors in the infrared and also in the visible.

9909-42, Session 11

AO WFS detector developments at ESO to prepare for the E-ELT

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ESO has a very active on-going AO WFS detector development program to not only meet the needs of the current crop of instruments for the VLT, but also has been actively involved in gathering requirements, planning, and developing detectors and controllers/cameras for the challenging instruments in design and being proposed for the E-ELT.

This paper provides an overall summary of the AO WFS sensor requirements of the various E-ELT instruments and AO Adapters. This is followed by a description of the many interesting detector, controller and camera developments underway at ESO to meet these needs; a) the rationale behind and plan to upgrade the 240x240 pixels, 2000fps, "zero noise", L3Vision CCD220 sensor based AONGC camera; b) status of the LGSD/NGSD High QE, 3e- RoN, fast 700fps, 1760x1680 pixels, AO LGS CMOS Imager and camera development; c) status of and development plans for the Selex SAPHIRA IR eAPD and controller.

Most of the instruments and detector developments are described in more detail in other papers at this conference.

9909-43, Session 11

Near infrared wavefront sensing

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We discuss the advantages of wavefront sensing at near-infrared wavelengths, from low order sensing with laser guide star (LGS) adaptive optics (AO) to high order sensing with natural guide star (NGS) AO. We then turn to the application of near-infrared sensing with the Keck AO systems as a demonstrator for similar systems on extremely large telescopes (ELTs).

Near-infrared wavefront sensing is a critical enabling technology for science with adaptive optics (AO) on current and future telescopes. It will enable high contrast science of exoplanets around low-mass stars and dust obscured regions (e.g. star-forming regions and the Galactic Center), and high sky coverage for extragalactic science. It can be used to extend the performance of NGS AO to fainter (i.e. redder) targets and to increase the sky coverage of LGS AO. Furthermore, it allows the application of optimal wavefront sensing approaches (e.g. pyramid and Zernike wavefront sensing) due to the AO correction at near-infrared wavelengths. All of the extremely large telescopes (ELTs) are planning to use infrared wavefront sensing as part of their AO facilities. The development and on-sky demonstration of near-infrared wavefront sensing represents considerable risk reduction for these projects. Furthermore all of the ELTs are segmented telescopes and the Keck telescopes with their AO systems are the only viable platform to evaluate any interaction issues between a segmented mirror and high order infrared wavefront sensing.

Game-changing sub-electron readout noise near-infrared detector technologies have recently become available; specifically the Selex SAPHIRA, and potentially the CEA/Sofradir RAPID, avalanche photo-diode arrays for high or low order sensing, and multiple reads of the Teledyne Hawaii (HxRG) detectors for low order sensing. We will report on our collaborative efforts to demonstrate both low and high order wavefront sensing using these technologies. These efforts include:

• University of Hawaii's work with Selex to develop and characterize the SAPHIRA array and the implementation of a traveling test camera.

• French (i.e. First Light Inc. (FLI), Institut d'Astrophysique et Planetologie a Grenoble (IPAG), Laboratoire d'Astrophysique de Marseille (LAM) and ONERA) work on detector and camera development.

• The extension of the pyramid wavefront sensor (PWFS) expertise at Arcetri and Subaru, including the real-time software used with the SCExAO's visible PWFS, to near-infrared PWFS.

• Implementation of a H2RG based tip-tilt sensor with the Keck I LGS AO system and enhancements to this system, including multiple tip-tilt stars.

• Application of a low order (e.g. focus) sensing algorithm (i.e. LIFT) to a near-infrared tip-tilt sensor system.

• Simulations and modeling of both low and high order near-infrared wavefront sensing.

• The proposed development of a near-infrared PWFS for on-sky demonstration with the Keck II AO system. The demonstration would include a pilot L-band coronagraphic imaging survey of 150 M dwarfs to identify exoplanet candidates around these host stars for the first time, followed by spectroscopy of these exoplanet candidates.

9909-44, Session 12

Tackling down the low-wind effect with SAXO, the SPHERE eXtreme Adaptive Optics system

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SPHERE is the VLT second generation planet hunter instrument. Installed since may 2014 on UT3, the system has been commissionned and verified for more than one year now and routinely delivers unprecedented images of star surroundings, exoplanets and dust disks. The exceptionnal performance required for this kind of observation makes the appointment: a repeatable Strehl Ratio of 90% in H band, a rough contrast level of 10-5@0.5 arcsec, and reaches 10-6 at the same separation after differential imaging (SDI, ADI). The instrument also presents high contrast levels in the visible and an unprecedented 17mas diffraction-limited resolution at 0.65 microns wavelength. SAXO is the SPHERE XAO system, allowing the system to reach its final detectivity. Its high performance and therefore highly sensitive capacities turns a new eye on telescope environement.

SAXO and SPHERE allowed to diagnose an effect called "Low Wind Effect", degrading strongly the performance of the SPHERE instrument during low wind atmospherical conditions. Some wave-front aberrations have been identified, composed of strong segmented contributions and deviating from kolmogorov statistics, and therefore not easily seen and compensated for by the XAO system. Solutions are developped and tested on sky to propose a new operation procedure reducing this limitation. The measurement of these particular aberrations is made with a dedicated phase diversity algorithm, while the compensation is proposed to be made with the SAXO loop as a classical Non Common Path aberration. The performance of this solution is studied in simulation, we present the first on-sky implementation of the method.

9909-45, Session 12

Coronagraphic imaging of habitable exoplanets with large ground-based telescopes: fundamental limits and system architecture

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Thanks to recent advances in coronagraphy, detector technology, deformable mirrors and wavefront sensing techniques, we show that direct imaging and spectroscopic characterization of rocky planets in the habitable zones of nearby stars will be within reach of future 25-40-m extremely-large telescopes (ELTs). High throughput coronagraph designs compatible with segmented apertures enable efficient broadband imaging as close as 1 l/D from the star, and can be optimized to operate on partially resolved targets (nearby stars). New wavefront sensing approaches, such as unmodulated pyramid WFS, operate at the diffraction limit of the telescope and offer several order magnitude improvements in sensitivity over current seeing-limited sensors. Focal-plane wavefront sensing can provide immunity from non-common path errors limiting current systems, together with the ability to separate coherent speckles from incoherent planet light. These approaches are benefiting from high speed high efficiency photon-counting detectors now or soon available at visible and near-infrared wavelengths. Laboratory and on-sky demonstrations of these key techniques are being conducted, and will be reviewed.

We quantitatively derive the high contrast imaging performance of large ground-based telescope, and explore/compare several system architectures. We start with a physical model of atmospheric turbulence, capturing the temporal and chromatic dependency of incoming wavefronts. The model takes into account atmospheric composition, chromatic refraction, scintillations and diffraction propagation. We then evaluate how combinations of wavefront sensors operating at multiple wavelengths and at multiple locations in the instrument can simultaneously drive a fast extreme-AO correction and maintain a high contrast area in the focal plane image. We also evaluate the sensitivity gain offered by predictive control of atmospheric wavefronts. Finally, we explore how focal plane speckle sensing and modulation can calibrate residual speckles to better uncover planet light, which is incoherent with the central star.

We identify science targets and instrument system architectures suitable for reflected light imaging and spectroscopy of habitable planets around nearby stars in visible and near-IR. We conclude that ELTs can reach the sensitivity to image and characterize habitable planets around approximately 50 stars. We discuss how the technology gap between our assumptions and the current state of the art can be filled over the next few years, and possible future enhancements to our proposed approach.

9909-46, Session 12

Evolutionary timescales of AO-produced speckles at NIR wavelengths

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In order to observe in reflected light potentially habitable exoplanets, advanced wavefront control techniques must be developed and implemented. Effects such as imperfect AO correction of atmospheric turbulence, diffraction within the optical system, etc. produce a “speckle halo” around the PSF. These speckles, which have intensities up to a few 10^-3 times that of the PSF core, evolve with timescales that have not previously been characterized at near-infrared (NIR) wavelengths. Because speckles can appear indistinguishable from stellar companions such as exoplanets, they must be understood and removed. In order to better understand the behavior of these speckles and make informed decisions about future speckle control loops, we present measurements of the evolutionary timescales of speckles around adaptive optics-corrected PSFs. We placed a SELEX SAPHIRA 320x256 HgCdTe infrared APD detector behind the SCExAO instrument at Subaru Telescope atop Mauna Kea, Hawaii. SCExAO provides a 2000-element deformable mirror updating at 3.5 kHz for extreme adaptive optics corrections (NIR Strehls > 80%). We observed unresolved stars and analyzed the behavior of speckles at 1-10 ?/D from the PSF core in H-band (~1.6 ?m) SAPHIRA images collected at a frame rate of ~1 kHz. Ultimately we would like to image in reflected light potentially habitable exoplanets around nearby stars. These have typical contrasts ranging from 10^-7 (a rocky planet around an M-type star, potentially accessible with 30m-class telescopes) to 10^-10 (Earth around Sun-like star), independent of wavelength. Achieving this ambitious goal necessitates a fast speckle control loop that is able to (1) reduce speckle raw intensities, and (2) calibrate in post-processing residual speckles in order to separate them from incoherent planet light. We apply our measured speckle evolutionary timescales to derive the performance parameters of a speckle control loop optimized for this application. On Subaru Telescope, this activity will lead to direct imaging in reflected light of giant planets, in preparation for habitable planet imaging and spectroscopic characterization with 30m-class telescopes.

9909-224, Session PWed1

Precision astrometry with adaptive optics: towards exoplanet mass measurement from the ground

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ELTs equipped with MCAO systems will be powerful astrometric tools in the next two decades. With sparse-field precisions exceeding 30 uas for V > 18, the ELTs will surpass even GAIA’s per-epoch precision for faint stars (V > 12). We present results from three ongoing astrometry programs with Keck NIRC2, Gemini GeMS, and ShaneAO and discuss synergies with WFIRST and GAIA. We present the first direct mass measurements of the individual L/T components of Luhman16 AB, the nearest brown dwarf binary known. Exploiting GeMS’ wide field of view to image reference stars, we are able to track the barycenter motion to better than 0.5 mas and derive the stellar masses with 3% precision, enabling a rigorous calibration of evolutionary models. We find that a mutual Keplerian orbit with no perturbing planets fits the binary separation to within the measurement errors, ruling out companions down to 14 earth masses for certain orbits.

We also present results from 2 years of astrometric monitoring of 15 T dwarfs with Keck NIRC2 and ShaneAO. With astrometric precisions of ~0.3 mas, we probe the brown dwarfs for companions as small as Saturn over 0.3- 2.0 year periods. The resulting limit on the giant planet occurrence rate independently checks planet formation models at the extreme low-mass end of the stellar main sequence.

Third, we show on-sky results with a lithographically-imprinted diffractive mask installed in the ShaneAO adaptive optics system. We verify that the diffractive mask allows us to recover astrometry of otherwise saturated bright stars at the ~0.3 mas level while simultaneously imaging field reference stars with high precision. Such a capability will be important for directly measuring masses of exoplanets discovered with GPI/SPHERE such as 51 Eri, independently calibrating planet formation models.

9909-226, Session PWed1

The Robo-AO KOI survey: laser adaptive optics imaging of every Kepler exoplanet candidate

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The Robo-AO Kepler Planetary Candidate Survey is observing every Kepler

planet candidate host star (KOI) with laser adaptive optics imaging to hunt for blended nearby stars which may be physically associated companions. With the unparalleled efficiency provided by the first fully robotic adaptive optics system, we perform the critical search for nearby stars (0.15" to 4.0" separation with contrasts up to 6 magnitudes) that dilute the observed planetary transit signal, contributing to inaccurate planetary characteristics or astrophysical false positives. We present approximately 3300 high resolution observations of Kepler planetary hosts from 2012-2015, with ~500 observed nearby stars. We measure an overall nearby star probability rate of 16.2±0.8%. With this large data set, we are uniquely able to explore broad correlations between multiple star systems and the properties of the planets which they host, providing insight into the formation and evolution of planetary systems in our galaxy. Several KOIs of particular interest will be discussed, including possible quadruple star systems hosting planets and updated properties for possible rocky planets orbiting with in their star's habitable zone. Other Robo-AO surveys will also be presented.

9909-228, Session PWed1

GeMS/GSAOI photometric performances from an user perspective

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Ground-based near-IR imagers assisted by MCAO systems are the technological frontier to obtain high-quality stellar photometry in crowded fields at the highest possible spatial resolution. GeMS/GSAOI is the only MCAO system currently offered to the astronomical community.

We used a large sample of globular cluster images obtained in the J and Ks bands with GeMS/GSAOI under significantly different atmospheric conditions, to characterize the properties of the PSF (Full Width Half Maximum, Strehl Ratio, Encircled Energy) across the field of view as a function of the seeing.

We also performed some comparisons with images of the same targets obtained with ACS/WFC onboard HST.

9909-230, Session PWed1

Combining high-angular resolution imaging with state of the art 3D observations of distant galaxies

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In this paper we present first results on observations of a galaxy group at z~0.7, dissected both with high-angular resolution Near-Infrared images and 3D spectroscopy. The imaging part has been acquired with the newly GeMS/GSAOI instrument at Gemini South. This instrument provides high-angular resolution images in the NIR. For our observations, we obtained deep K-band images with a resolution of ~70mas. The unique performance and Field of View (FoV) provided by GeMS/GSAOI is used to derive an accurate and unprecedented morphological analysis of the group's galaxies. At these redshifts the GeMS/GSAOI NIR images are critical to determine the morphologies as they probe the old, underlying stellar populations that trace the bulk of the galaxy stellar mass and avoid bias due to young stellar formation. This unique morphological information is then combined with resolved internal derived from 3D spectroscopy. Two galaxies of the field already benefit from VLT/SINFONI observations, and the whole field has been observed with the MUSE instrument, a new generation 3D spectrograph at the ESO-VLT. By combining high resolution morphology, and kinematics, we will establish a complete description and understanding on the process at work in each individual galaxy studied, and investigate in great details how galaxies transform in specific group environments.

9909-232, Session PWed1

Astrometry with spatially variable PSFs: instrumental field-dependent aberrations

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Near infrared adaptive optics observations of the Galactic Center with the Keck Telescopes have revealed the presence of a supermassive black hole by tracing the orbits of the stars in the innermost arcsecond. The closest approach of S0-2--a bright, well-studied star that is expected to get within 130 mas of Sgr A*—in 2018 provides us with a unique opportunity to test General Relativity in the strong-gravity regime. Our current astrometry extraction techniques utilize StarFinder (Diolaiti et al. 2000), but this software does not take into account instrumental aberrations or atmospheric anisoplanatism that may affect spatial variability of the PSF. The Galactic Center Group at UCLA is in the final year of developing a software package that works with existing StarFinder modules to predict how the PSF varies off-axis and takes into account both instrumental and atmospheric anisoplanatic aberrations.

We present a model for 21 Zernike terms of field-dependent aberrations arising in the NIRC2 and OSIRIS infrared imagers on the W. M. Keck Telescopes. We use high signal-to-noise ratio phase diversity data employing a lit fiber source in the Nasmyth focal plane for each instrument to construct models of the optical path difference as a function of field position across the detector. With a differential wavefront error of up to 220 nm in NIRC2 and 100 nm in OSIRIS, this effect is a main contributor to astrometric and photometric measurement uncertainties, and can affect the astrometry up to 2 mas, which is large compared to our overall astrometric error of ~3 mas. The stability over a two-year period of our grid was 60 nm RMS, still significantly less than the overall wavefront error. The sampling error, measured from looking at the differences between adjacent maps, is highest at distances furthest from the optical axis (up to 87 nm

RMS), and has an average wavefront error difference of 43 nm RMS.

To apply a continuous model of the instrumental aberrations, we construct a third-order spline interpolated model constructed for the first 21 Zernike coefficients across the field of view of the detector. The difference between the model and measured phase maps at various points across our detector is at most 40 nm RMS. This model has been incorporated into the AIROPA (Anisoplanatic and Instrumental Reconstruction of Off-axis PSFs for AO) software package, and the details on the algorithms, data acquisition, and data reduction techniques are incorporated and can be applied on most systems that have tools (i.e., a moveable lit fiber) similar to NIRC2 and OSIRIS.

9909-234, Session PWed1

High-z galaxies simulations: a benchmark for GMCAO

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The superb spatial resolution of next generation ELTs gives the possibility to study far objects and to puzzle over the complexities of one of the key questions of the extragalactic research in the last years: how galaxies formed and evolved. The paramount controversy is about which scenario is more eligible between the “monolithic” process, in which large proto-galaxies formed early through a dissipational collapse, and the “hierarchical” one, in which galaxies are the result of successive mergers between small structures.

Several astronomical surveys that investigate the galactic structures over a wide range of morphologies were carried out in order to discriminate between the two scenarios. This kind of study needs an excellent level of details, possible only with space telescopes or with the application of adaptive optics techniques for ground-based ELTs.

In this work we supported the innovative idea of a Global-MCAO system that maximizes the chance to find suitable reference stars in a wide field of view, a fundamental issue for the forthcoming E-ELT. Therefore GMCAO allows the development of extragalactic research with ground-based instrumentation, often frozen out because of the small sky coverage. An estimation of the gain of this approach is given for several scientific results, and a thorough discussion is provided in order to assess the actual ability of GMCAO to deal with these classes of astrophysical problematic.

Moreover, using a tomographic simulation tool we compute a map of the Strehl Ratio simulating an observation of the Chandra Deep Field South with an ELT that makes use of the GMCAO. We take the E-ELT specifications as a reference and used them to build a mock image of a set of galaxies, assuming the estimated Strehl Ratio. The morphology and photometric properties of the sample galaxies were examined performing the source detection and two-dimensional light-profile modeling.

The good agreement we found between the recovered and the intrinsic parameters depicts GMCAO as a reliable challenging approach that can rebuild the AO skills and can cross the extragalactic frontiers to new unforeseen results.

9909-225, Session PWed2

Optical solutions for accommodating ELT LGS wavefront sensing to small format detectors

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Sodium laser guide stars (LGS) will be used on extremely large telescopes (ELT) for increasing the sky coverage of adaptive optics systems. The thickness of the sodium layer together with a perspective effect makes the laser beacon to appear as an elongated plume when observed from a pupil location distant from the laser launch telescope. The wave-front sensing with a Shack-Hartmann on such a peculiar object then requires a large number of pixels per sub-aperture in order to cope with the required field of view. As a large number of sub-apertures is required on an ELT, this results in the need for detector formats exceeding 1500x1500 pixels. It is worth noticing however that most of these numerous pixels are useless, as many of them won’t receive any light due to the arrangement of the pattern of spots.

We present in this article some potential optical solutions for reducing the requirements of the detector format by a significant amount. This is obtained by re-arranging the pattern of the elongated spots in order to avoid any loss of space between them. Depending on the geometry of the system, a factor of ≈2 on the pixel count can be gained along both directions.

9909-227, Session PWed2

A general formalism for Fourier-based wavefront sensing: application to the pyramid wavefront sensors

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In the article, we compare a set of Wave Front sensors based on Fourier filtering technique. In particular, this study explores the “class of pyramidal WFS” defined as the 4 faces pyramid WFS, all its recent variations (6, 8 faces, the flattened PWFS, etc.) and also some new WFSs as the flattened cone WFS or the 3 faces pyramid WFS.

In the first part, we introduce an analytic mathematical formalism based on Fresnel optics, which allows, among other things, to define a rigorous criterion about the chromaticity of a WFS. Secondly, we define an unified numerical post-imaging process which allows to avoid the constraining definition of the usual slopes maps computations (only valid for the PWFS).

We finally compare the WFSs of the Pyramidal class following a large set of criteria: efficiency of incoming flux, sensitivity, linear range, capacity to close a basic Adaptive Optics loop and chromaticity when the optical parameters of the Fourier filtering mask (number of faces, angle of the apex) change.

We show that the 3 faces pyramid has a very similar behavior compared with the 4 faces version.

We also show that the shape of the mask does not really matter on the performance when the angle of the apex is small, showing that the ease manufacturing may be the only relevant criterion to choose between these WFSs.

9909-229, Session PWed2

Sensing wavefronts on resolved sources with pyramids on ELTs

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The discussion about the advantages of Pyramid-type wavefront sensors (PWFS) with respect to Hartmann-Shack systems (SHS) is entering its second decade. It is nowadays widely recognized that Pyramid sensors do have an advantage at the faint end, being able to maintain peak performance on fainter stars than SHSs can. While this might render a choice between the two types for usage on ELT single-conjugate AO (SCAO) systems easy at first glance, particular concerns do exist: It is widely believed that PWFSs do require modulation to achieve optimal performance, something not necessarily easy to achieve in a cryogenic environment. On the other hand, SHSs require more pixels and thus larger detectors to optimally analyze a wavefront. A new concern arises however particularly on ELTs: This novel class of telescopes will, unsurprisingly, provide unprecedented resolution. Since much of the PWFSs advantages arises from the usage of the full telescope aperture, and thus its unrivaled resolution limit, it will now be confronted with an also unprecedented number of resolved reference sources.

While it is generally agreed that when using a resolved object for wavefront sensing, the PWFS' performance becomes equivalent to that of a SHS, systematic research on the behavior of a PWFS operating on extended sources is lacking to date. While observational proof exists that PWFSs do still work on extended targets, and performance roughly as expected, simulations of the subject are hard to come by. In observational data, the resulting Strehl ratio (SR) of an observation is not easy to measure correctly on an extended source. Objects that would provide an extened or even simply binary target as reference star with a suitably nearby point source to measure the resulting SR are also not abundant in the sky. Simulations are difficult, as tezhy require alrge amounts of computation time when each "pixel" of an extended source is propagated through the simulated WFS individually.

Nevertheless, in the course of a trade-off study for the METIS instrument for the E-ELT, we are conducting a large set of simulations of the performance of the PWFS option on multiple and extended sources. In this presentation, we will summarize the results and, for the first time, show quantitatively how a simulated yet real-world system is expected to behave on this class of reference objects.

9909-231, Session PWed2

ESO adaptive optics NGSD/LGSD detector and camera controller for the E-ELT

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This paper presents the details of the design of the first ESO Adaptive Optics (AO) camera and controller for the E-ELT which is based on the e2v large format CMOS imager Natural Guide Star Detector (NGSD) and Laser Guide Star Detector. NGSD is a 880x840 pixel CMOS array organized as 44x42 sub-apertures of 20x20 pixel each. NGSD is exactly 1/4 of the LGSD and therefore it is considered a scaled down demonstrator for the LGSD (1760x1680 pixels).

The detector controller requirements present numerous challenges in the design of the electronics due to the low-power, low-noise and high parallel data rate of the detectors involved.

The general architecture of the controller along with the front-end electronics to drive and read-out the detector are based on Xilinx Virtex-7 FPGAs and its advanced features as skew clock compensation, embedded CPUs and high-speed XAUI and 10 GbE interfaces, to name a few.

In addition, the work presented here describes both the modular and compact mechanical design approach, its built-in TEC controller, the environmental sensors and more importantly, the design roadmap for the future E-ELT AO camera based on this first version.

First tests results obtained with the camera and Rev. B of NGSD imager are here reported.

9909-233, Session PWed2

LIFT on Keck: analysis of performance and first experimental results

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Laser-assisted adaptive optics relies on natural guide stars for the estimation of low orders. Infrared wavefront sensors, compared to visible ones, provide some advantages for this application: lower wavefront distorsion, hence better sensitivity, and access to colder stars or stars behind dust clouds, hence higher sky coverage. Moreover, cold stars of type K or M, which emit more in the near infrared than in visible light (2 to 3 magnitudes difference), represent a great majority of main-sequence stars. However, visible wavefront sensors have been preferred until now because of the difference in noise level between visible and infrared detectors.

Recently, a H2RG-based camera was implemented with the Keck I laser guide star adaptive optics system to work as a near-infrared (H and/or Ks band) tip-tilt sensor. Low noise is achieved by multiple reads of small regions of interest. The on-sky results have been excellent and have motivated a proposal to implement a near-infrared low-order wavefront sensor on Keck II. The Keck II sensor will be based on the recent advances with HgCdTe avalanche photodiodes arrays, such as the SAPHIRA (Selex) and RAPID (CEA LETI/Sofradir) detectors, which offer very low noise (1 to few electrons), and thus wavefront sensing at low flux in the near infrared.

The recently developed low-order wavefront sensor algorithm LIFT is considered for this application. It is very simple to set up, as it makes its estimation from a single astigmatic focal image. Previous studies have shown that LIFT has good noise propagation properties, comparable to a non-modulated pyramid, for the estimation of tip/tilt and focus. It was validated in the lab and in open loop on sky with the Gemini South MCAO system GeMS.

We will report on tests performed to prepare an implementation of LIFT on the Keck telescopes. Astigmatic images of calibration sources were acquired on the H2RG camera in Ks band. In this configuration, the sampling is 0.45 times the Nyquist sampling. LIFT had only been validated at Nyquist sampling before, and the extension to strongly undersampled images is a key operational aspect. With these tests, we have demonstrated the successful estimation of focus and astigmatism ramps at such a low sampling. The next steps will be to verify LIFT's performance in the presence of simulated turbulence, and finally to demonstrate the first pseudo-closed loop operation of LIFT on sky.

In parallel with these experiments, we will evaluate LIFT's behavior on a Keck-like system with end-to-end simulations and compare these with experimental results. We will also compare the outcome of these simulations with similar work previously for a different configuration (Gemini-like system, Nyquist sampling) and discuss the utility of using LIFT at low sampling.

9909-235, Session PWed2

Experimental study of an optimised Pyramid wavefront sensor for extremely large telescopes

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Over the last few years the Laboratoire d'Astrophysique de Marseille (LAM) has been heavily involved in R&D for adaptive optics systems dedicated to future large telescopes, particularly in preparation for the European Extremely Large Telescope (E-ELT). Within this framework an investigation into a Pyramid wave-front sensor is underway. The Pyramid sensor is at the cutting edge of high order, high precision wave-front sensing for ground based telescopes. Investigations have demonstrated the ability to achieve a greater sensitivity than the standard Shack-Hartmann wave-front sensor whilst the implementation of a Pyramid sensor on the Large Binocular Telescope (LBT) has provided compelling results.

The Pyramid now forms part of the baseline for several next generation Extremely Large Telescopes (ELTs). As such its behaviour under realistic operating conditions must be further understood in order to optimise performance. At LAM a detailed investigation into the performance of the Pyramid aims to fully characterise the behaviour of this wave-front sensor in terms of linearity, sensitivity and dynamic range. We have implemented a Pyramid sensor using a high speed OCAM2 camera (incorporating close to 0 readout noise with a high frame rate of 1.5kHz), with which we carry out a study of the performance in a full closed loop adaptive optics system. This investigation involves tests on all fronts: from theoretical models and numerical simulations; to experimental tests under controlled laboratory conditions, with an aim to fully understand the Pyramid sensor in both modulated and non-modulated configurations. We include results demonstrating the linearity of the Pyramid signals; compare measured interaction matrices for different methods of calculating the 'meta-intensities'; and compare the Pyramid performance under modal and zonal control. The final goal is to provide an on sky comparison between the Pyramid and a Shack-Hartmann wave-front sensor, at Observatoire de la Côte d'Azur (ONERA-ODISSEE bench) during the first half of 2016. Here we present our setup and latest experimental and modelling results.

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Novel tip-tilt sensing strategies for the laser tomography adaptive optics system of the GMT

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The availability of suitable tip-tilt guide stars is usually limits both the Strehl ratio and the sky coverage of laser guide star adaptive optics systems. The emergence of infrared eAPD arrays allows fast, low-noise tip-tilt sensing at wavelengths where the wavefront is partially corrected. For off-axis tip-tilt sensing, we show that the centroid estimator produces large errors even when there is no noise. Instead, we demonstrate that a peak finding algorithm, such as the correlation algorithm, leads to Strehl maximimizing tip-tilt estimates. In the case of the GMT, the sky coverage can be increased by supplementing low frame rate infrared tip-tilt measurements on a faint, near on-axis star with fast visible light measurements on bright guide stars 6 to 10 arcminutes off-axis.

9909-237, Session PWed2

Comparative study of infrared wavefront sensing solutions for adaptive optics

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Adaptive optics systems in astronomy mostly rely on visible wavefront sensing for the analysis on natural guide stars, although infrared sensing would provide some advantages: lower wavefront distorsion, hence better sensitivity, and access to colder stars or stars behind dust clouds, hence higher sky coverage. This choice has been driven by the detectors technology: current visible detectors are almost noiseless, while classical infrared detectors suffer from high noise levels. The development of new infrared detectors based on HgCdTe avalanche photodiodes, such as RAPID (CEA LETI/Sofradir) or SAPHIRA (Selex), has given the possibility to detect infrared light with a detector noise low enough (1 to few electrons) to consider wavefront sensing at low flux.

On the other hand, whereas the Shack-Hartmann sensor can be found in almost every adaptive optics system, recent and promising wavefront sensing concepts, such as the pyramid sensor or the quadri-wave lateral shearing interferometer, are rarely used. It has been shown that the pyramid has a better behavior than the Shack-Hartmann in terms of noise propagation and aliasing. The quadri-wave lateral shearing interferometer has not been studied thoroughly yet in this context, but it also has the potential to overperform the Shack-Hartmann, while offering the possibility of a trade-off between sensitivity and dynamic range, as the pyramid does.

We propose here a comparative study of near infrared (J and H bands) wavefront sensing concepts using the RAPID camera, for mid and high orders estimation on an 8m-class telescope. These concepts rely on the three previously cited wavefront sensors: the Shack-Hartmann sensor, the pyramid sensor and the quadri-wave lateral shearing interferometer. All three of them rely on a simple optical element (microlens array, pyramid or self-imaging grating) that could be integrated in a DDCA (Detector Dewar Cooler Assembly), i.e. the cryogenic environment of the detector, for an optimal limitation of background and straylight.

An important point of this study is the trade-off between the noise level, linked to the background flux, and the compactness/realization difficulty of the DDCA. We present several preliminary designs, with optical elements being inside or outside the DDCA, and discuss on the main parameters that have an impact on background flux and on the DDCA itself.

To better evaluate the impact of background flux, and compare the relative performance of the different concepts, we also determine their respective noise propagation. This is done thanks to previous works relying on precise diffractive models.

Finally, we conclude on the main points that have to be considered for future infrared wavefront sensor designs, and propose a design basis that will be developed in future works.

9909-238, Session PWed2

Pupil phase discontinuity measurement: WFS sensing approach

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Segmented deformable mirrors are widely used today in several domains: fiber bundle coupling, laser beam shaping, microscopy, retina imaging and many other applications such as wavefront control of LGS beam, Fibered Imager for Single Telescope.

In astronomy, and more particularly in the era of the giant telescopes, segmented deformable mirrors are mainly used to simulate bigger mirror sizes but also offer solutions for other questions related to fabrication, optics replacement and transport. In all its appliactions, they raise the problem of segment cophasing, characterization and measurement of phase discontinuities between segments.

In the E-ELT frame work, the Laboratoire d'Astrophysique de Marseille (LAM) is developing several R&D activities for active and adaptive optics instrumentation. Indeed, besides being at the origin of the development of the OCAM2 camera, a state of the art detector (up to 2.2 kHz frame rate and RON close to zero) and the demonstration of an ESO-EELT M1 mirror segment (1.5 m), our institute is deeply involved in the design of SCAO (Single Conjugated Adaptive Optics) and LTAO (Laser Tomography Adaptive Optics) systems for the HARMONI first light instrument.. We also develop since several years different wavefront sensing concepts such as the Pyramis sensor (OCAM2-Pyramid), the Zernike phase mask sensor (ZELDA), Phase diversity and NL Curvature.

In the present work, we couple a segmented mirror from Iris AO (PTT111, three degrees of freedom per segment) with different wavefront sensors: Shack-Hartmann, Pyramid and ZELDA. We aim to study their sensitivity to a segmented pupil and propose a suitable wavefront sensing approach for phase discontinuity measurements: segment phasing, stability, saturation, flat. Different addressing modes are then tested.

9909-239, Session PWed2

Correction of NIRI/ Altair non-common path aberrations using focal plane sharpening

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Adaptive optics, in astronomy, have been developed over the last 60+ years to help mitigate the degradational effects of turbulence in the atmosphere on image quality. As the index of refraction in earth's atmosphere changes spatially and temporally with temperature and wind speed variations, the wavefronts of light traversing through the atmosphere are blurred. In principle, a deformable optical element is used in conjunction with a wavefront sensor to provide near real-time corrections to the wavefront and output an un-aberrated phase to the science instrument(s). However, since the science instruments themselves inevitably introduce their own optical aberrations, there is a need for the deformable element to output a wavefront that is not necessarily aberration free, but rather inverse in phase to the aberrations inherent to the instrument. At the Gemini North Observatory, on the adaptive optics facility ALTAIR, accounting for these static non-common path aberrations could improve the K-band strehl ratio by as much as 30% on the near-infrared imaging instrument, NIRI. A technique known as focal plane sharpening is employed to correct for these non-common light path aberrations in NIRI. Small changes in the shape of the deformable mirror are made iteratively via a simplex algorithm as images of a light source in the shared light path are taken and analyzed in order to determine the best delivered image quality and therefore correct for the non-common path aberrations.

9909-240, Session PWed2

Wavefront sensing using a photonic lantern

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The need for high speed wavefront sensing within astronomical adaptive optics (AO) is growing, especially with the coming Extremely Large Telescope (ELT) scales. Wavefront sensors (WFSs), such as the Shack-Hartmann, typically rely on using a large 2D detector array to sample sufficient spatial frequencies at rates that can allow AO correction. At ELT scales these detectors must be developed specifically for wavefront sensing, greatly increasing system cost. In addition, handling the large data rates and processing pixel data in real time introduces a large computational overhead to the system. One potential solution to this problem could be made possible by using a photonic lantern (PL) as a WFS. The PL efficiently reformats a multi-moded input fibre to a set of single modes, all guided within individual fibres. The intensity output from each single mode fibre provides an optical modal decomposition of the PSF coupled into the input multi-mode fibre. A final design of a PL will therefore only require a 1D CCD array or individual low-noise photodiodes to measure the intensity distribution of each single mode output of the lantern. Not only could wavefront sensing with a PL remove the requirement for a large CCD array, but the read out speeds of a 1D array are much faster (by roughly an order of magnitude) and suitable low read noise devices already exist. In addition, without the need for complex centroiding such as in a Shack-Hartmann, the PL WFS only relies on the output intensities and could be relatively computationally inexpensive. We have developed an experimental set up using a 32-actuator Boston Mini-DM and an ultra-fast laser inscribed PL provided by Heriot-Watt University. Here we present results investigating the coupling between low-order aberrated wavefronts and the multimode input of the PL by analysing output of the separated single mode cores to investigate the suitability of a PL as an integrated wavefront sensing device. We also discuss the orthogonality of input wavefront and PL propagated modes.

9909-242, Session PWed2

High order dark wavefront sensing simulations

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Dark wavefront sensing takes shape following quantum mechanics concepts in which one is able to "see" an object in one path of a two arm interferometer using an as low as desired amount of light actually "hitting" the occulting object. A theoretical way to achieve such a goal is represented by a combination of two unequal beams interferometer sharing the same incoming light, and whose difference in path length is continuously adjusted in order to show different signals for different signs of the incoming perturbation. Furthermore, in order to obtain this in white light, the path difference should be properly adjusted vs the wavelength used. While we incidentally describe how this could be achieved in a true opto-mechanical setup, we focus our attention to the simulation of an hypothetical "perfect" dark wavefront sensor of this kind in which white

light compensation is accomplished in a perfect manner and the gain is automatically tuned to the very best. Although this would represent a sort of idealized dark wavefront sensor that would probably be hard to match in real glass and metal, it would also give a firm indication of the maximum achievable gain or, in other words, of the prize for achieving such device. We compare this dark sensor to a conventional one in closed loop performing numerical simulation of both analyzing the behaviors and the performance on a common conventional adaptive optics system and a Kolmogorov turbulence evolving with time.

9909-243, Session PWed2

LGS wavefront sensing: pyramid and SH sensor comparison

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Laser Guide Star (LGS) reference sources, artificially generated at an altitude of 90 km at the atmospheric sodium layer, are mandatory to ensure large sky coverage of astronomical Adaptive Optics (AO) systems developed for 8m and Extremely Large Telescope (ELT). As a result of the projection effect, being the laser spots located at a finite distance from the telescope, the AO wavefront sensors perceive the LGSs as elongated. This elongation is a few arcseconds for the 8m class telescopes and can be more than 15 arcseconds for the ELTs. This can pose several challenges when using a Shack-Hartmann (SH) sensor such as truncation effects, the requirement for large detectors, and/or the requirement for detectors with geometry that corresponds to the source shape. In this work, we report the results of numerical simulations focused on the use of a Pyramid sensor with LGS. In particular the simulations will take into account the extension in altitude of the reference star and its effects on the sensor behavior. A first part of the work is dedicated to the study of Noise Propagation Coefficients of an LGS based Pyramid WaveFront Sensor. Informations from such study are used to optimize the sensor configuration. A second part reports performance comparison of AO correction when PWFS or SHS are used with LGS under the same conditions for an 8m class telescope. Finally some example cases are shown for the AO correction of an ELT class telescope.

9909-245, Session PWed2

A fast and furious solution to the low-wind effect at SPHERE

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The SPHERE high-contrast imager for the VLT has recently finished its commissioning phase and is already providing exceptional results in the field of direct exoplanet and circumstellar disk imaging. Instrument performance is sometimes limited under the best seeing conditions by the so-called Low-Wind Effect (LWE), whereby the un-occulted stellar PSF gains two or more sidelobes (a.k.a. "Mickey Mouse ears") on spatial scales of 1 to 4 lambda/D and contrasts of 0.1 or greater, thus degrading the final coronagraph performance. In the pupil-plane this effect manifests itself as strong phase discontinuities and differential tip-tilt wavefront components within each pupil quadrant, which may reach 800nm in amplitude and are invisible to the filtered Shack-Hartmann Wavefront Sensor.

We present a potential noninvasive solution to sensing of the LWE wavefront, based on the "Fast and Furious" (F&F) sequential phase diversity wavefront reconstruction algorithm (Keller et al. 2014, Korkiakoski et al. 2014). This uses noncoronagraphic focal-plane images available from the NIR Differential Tip-Tilt Sensor and closed-loop DM update cycle telemetry to reconstruct the complex wavefront. Crucially, this removes the need for artificial phase probes on the DM itself as is the case for standard phase diversity approaches, allowing the technique to be performed as part of the AO closed-loop. Preliminary simulations indicate accurate recovery of the LWE wavefront shape and effective removal of LWE PSF lobes within a small number of F&F iterations. We will present the results of efforts to optimise this algorithm to the LWE on SPHERE, with the ultimate goal of integration within the SAXO closed-loop environment to detect and eliminate the LWE as it arises.

9909-246, Session PWed2

Focal plane wave-front sensing on phase discontinuities: from SPHERE to ELT high-contrast imagers

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Classic adaptive optics (AO) has evolved considerably over the past few decades, driving the development for complex technologies such as high-contrast imaging; the recent commissioning of the SPHERE and GPI instruments on the VLT and Gemini telescopes have delivered the first top level instruments dedicated to this technology. Most future ground based telescopes (E-ELT, TMT, GMT) and space telescopes (JWST) will utilize segmented pupil shapes, which is a deflection from the plain pupils of the current telescopes that employ high-contrast imagers.

Among the limitations of high-contrast imagers are non-common path aberrations (NCPA), which result from the inability of the wavefront sensor to detect minute variations in the internal PSF of the imaging system. If these aberrations are not compensated, the AO loop cannot provide a correction and the focal plane is contaminated with NCPA residuals. We present new results on the calibration of NCPA for a coronographic (high-contrast imaging) system, in particular advances on the traditional NCPA correction techniques (i.e. phase diversity), which can be subject to errors when considering a segmented pupil instead of the traditional uniform case due to the phase discontinuities between each segment. We present new ideas and laboratory work on the calibration of aberrations resulting from a segmented pupil; in particular we examine these aberrations in both the coronographic and classical scenario, extending well known techniques such as phase diversity and focal plane sharpening.

9909-247, Session PWed2

Noncommon path aberration correction techniques and performances: handling multiple configuration AO systems

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Non-common path aberrations (NCPA) arise from optical path differences between the science camera and the wavefront sensor, resulting in focal plane residuals after the loop is closed on an AO system. We have established two methods of NCPA compensation techniques, and successfully demonstrated their qualities on an experimental bench at NRC-Herzberg (in Victoria, Canada). The advantages and disadvantages of each method are explored quantitatively, with the goal to determine if

there is a synergic combination between the methods to yield the most efficient NCPA calibration possible. The quantitative analysis includes an assessment (for a given AO system), of how many modes can be corrected, what initial conditions (i.e. starting wavefront error) work best with each method, and what combination of the two methods yields a correction with the lowest RMS wavefront error.

AO systems such as TMT's NFIRAOS will provide AO-corrected light to several instruments, with each configuration containing their own respective NCPA. We present a novel technique where an NCPA 'lookup' table is constructed in order to correct errors that reoccur when AO systems cycle through different configurations. This technique is explored on our experimental bench, where the reoccurring NCPA are created using two phase screens in the non-common pupil plane: one stationary and the other with rotation capabilities. The goal is to use our NCPA estimation methods to construct a table with estimations at various phase screen positions and demonstrate the table can be used to provide correction at any desired phase screen configuration.

9909-248, Session PWed2

A new look at the laser propagation delay as a tool to retrieve tipt-tilt information from a laser guide star

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As it is very well known nowadays Laser Guide Stars (LGS) are not useful to retrieve tip-tilt information. It seems to be general consensus that the onlypractical way to retrieve tipt-tilt in the Field of View of a telescope using LGS-assisted Adaptive Optics. However, there is been a time where such a resignation was fighted against by a large amount of ideas, concept, and actual true on-sky experiments. While some of the further studies in fact points toward the pragmatic –but not necessarily optimum- choice of simply look for enough bright natural references, we believe that one of the technique that has not been the subject of any further investigation could turn out of some relevance. We specifically refer to the so-called propagation delay in which the LGS is observed through the same aperture used to propagate. This would translates into nil jitter, but in fact it is easy to show that it would exhibits a small, but not negligible, finite difference with respect ot the time of traveling upward and backward. This difference can be integrated and used, till the accumulating error become below a certain threeshold, to guide an high frequency correction, and then being offset at low temporal frequency, by a true natural guide star. Once can see this as a multiplicator of bandwidth and in fact obtaining, for istance, 100Hz information from a natural star sampled at 1Hz –following the example given in the first and only paper on the subject) achieving a gain of 5 magnitude in limiting magnitude. The approach, in fact, continue to also use the advantages of the other technique for achieving high quality tip-tilt sensing (like the dark one). We revise the concept decribing its performance in a more detailed form, with a first order simulation and describing possible experimental setup to validate the approach with existing Sodium layer sounding facility.

9909-249, Session PWed2

Fast modulation and dithering on a pyramid wavefront sensor bench

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A pyramid wavefront sensor bench has been setup at NRC Herzberg (Victoria, Canada) to investigate, first, the feasibility of a lenslet-based pyramid wavefront sensor, and second, the proposed methodology for pyramid wavefront sensing to be used in NFIRAOS for the Thirty Meter Telescope. Traditional pyramid wavefront sensors require shallow angles and strict apex tolerances, making them difficult to manufacture. Lenslet arrays, on the other hand, are common optical components that can be made to the desired specifications, thus making them readily available. Understanding the differences between the two will allow for the lenslet-based pyramid wavefront sensor to become more widely used as an alternative to the standard pyramid, especially in a laboratory setting. In this work, the response of the SUSS microOptics 300-4.7 array, as the amount of modulation is changed, is compared to an ideal pyramid wavefront sensor modelled using the adaptive optics toolbox, OOMAO in MATLAB. The object oriented toolbox uses physical optics to model complete AO systems. Fast modulation and dithering using a PI fast steering mirror has been implemented using an Atmel mirco-controller to drive the mirror and trigger the camera exposure. This scheme allows for synchronization of the camera with the modulation, allowing for the linearity of the wavefront sensor to be increased. Applying a dithering signal, at a frequency of ? the modulation frequency, on top of the modulation signal allows for the optical gain to be tracked in real time, bettering the non-common path corrections. The various trade offs of this scheme, in a controlled laboratory environment, are studied and reported.

9909-250, Session PWed2

PWFSs on GMCAO: a different approach to the non-linearity issue

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In the last years, the Pyramid WFS (P-WFS) finally proved itself to be a very powerful tool for wavefront retrieval, in different applications, inside and outside astronomy, often showing outstanding results. However, being intrinsically a non-linear WFS, the P-WFS non-linearity error starts to play a role when the AO loop is not closed on the sensor zero-WFE point. This led to the need to elaborate new concepts when trying to apply the P-WFS to open (or partially open) loop based techniques, not to trade sensitivity for linearity. This was the case for Global MCAO, in which the reference stars are selected on a wide technical area of the sky, outside the FoV to be optimized, limiting the correction experienced by the WFSs to poor Strehl Ratio regime. While, in the recent past, we proposed a solution based on the Very Linear WFS, a sub-system that locally closes the loop on the Pyramid pin to let the sensor operate in its best regime, we now explore a different approach in which the PWFS non-linearity is continuously measured, injecting a known aberration onto the sensor. In particular, we evaluate in this paper the possibility to apply basic PWFSs to the GMCAO technique, measuring the non-linearity of the sensor and taking it into account in the wavefront computation, with an approach similar to what already proposed in the LBT AO facility FLAO for the non-common path aberrations correction.

9909-251, Session PWed2

An achromatic low-order wavefront sensor

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We propose an innovative Low-Order Wave-front Sensor (LOWFS) design based on the pyramidal wave-front sensor (PWFS). The four facets of a glass pyramid are equivalent to the intersection of four micro-lenses having the same focal length as the PWFS field lens. The intersection of the micro-lenses acts as the vertex of the pyramid. The main design parameters are then the focal length and the pitch of the micro-lenses which need to be chosen in order to prevent the overlap of the four sub-pupil images. We suggest placing such a 2 x 2 micro-lens array at the center of a coronagraph occulting mask. The micro-lenses are also reflective to relay the four sub-pupil images to an imaging sensor. A band-pass filter is placed in front of the imaging sensor to work at the same wavelength as the coronagraph scientific camera. The micro-lens mask is also circular cut or edge profiled to also acts as the coronagraph occulting mask. This novel PWFS approach could be an effective solution to counter the chromatic issues of other wave-front sensing schemes since the optical design is entirely reflective. The fabrication of micro-lenses is a well-established technology and could be an easy method to implement. It could also eliminate the need of additional optics in front of the LOWFS imaging detector, simplifying the design and helping to reduce or eliminate non-common path aberrations. We have developed a simulation package that allows to identify the basic physical requirements of a LOWFS based on a micro-lens mask and compute its performance in terms of linearity and sensitivity. Discussions with micro-lenses suppliers have permit to isolate the principal key design parameters and challenges.

9909-252, Session PWed2

Dark tip-tilt sensing

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Tip-tilt sensing of a diffraction limited natural guide star subjected in closed loop to limited movements could represent the last obstacle of Laser Guide Star based Adaptive Optics system on large and extremely large telescope, in practice setting up the ultimate performances of such systems. Peeling up its performances and reaching the as faint as possible magnitude limit become crucial into defining the performances in terms of achievable Strehl ratio and in sky coverage.

While it is interesting that such a basic way of wave-front sensing finally would turn out to be of such paramount relevance, we revisit the already pointed out fact that most of the light involved in the tip-tilt measurement in a quad-cell approach is actually producing noise and not contributing to the accuracy or sensitivity of the measurement. Specifically, under the class of "dark wave-front sensing", tip-tilt measurements (or, better, "dark tip-tilt sensing") aim to utilize just the smallest possible amount of photons contributing to the signal, while the vast majority being used for acquisition or to handle burst of jitter otherwise resulting into a loss of loop closure. The practical implementation of this approach does not involve any subtle diffraction limit effect, in contrast with similar realization for high order wave-front sensing. We can envisage a CCD with multiple dark spots of different size and placed at the crossroads of different groups of four adjacent pixels, with the sensor locking onto different ones to achieve the ultimate performance, depending upon the residual jitter.

We set up a number of realistic simulations using different combination of light split into a full quad-cell and clocked at different timescales in order to provide rapid re-acquisition in case of loss of lock due to a burst event in the jitter time series. Comparison of performances with respect to conventional quad-cell treated with the same kind of numerical approach are outlined along with the first crude conclusions for such a kind of first order dark wave-front sensing.

9909-253, Session PWed2

Sparse aperture differential piston measurements using the pyramid wavefront sensor

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In this paper we report on the laboratory experiment we settled in the Shanghai Astronomical Observatory (SHAO) to investigate the pyramid wave-front sensor (WFS) ability to measure the differential piston on a sparse aperture. The ultimate goal is to verify the ability of the pyramid WFS work in close loop to perform the phasing of the primary mirrors of a sparse Fizeau imaging telescope. In the experiment we installed on the optical bench we performed various test checking the ability to flat the wave-front using a deformable mirror and to measure the signal of the differential piston on a two pupils setup. These steps represent the background from which we start to perform full close loop operation on multiple apertures. These steps were also useful to characterize the achromatic double pyramids (double prisms) manufactured in the SHAO optical workshop.

9909-255, Session PWed2

Laser guide star spot shrinkage for affordable wavefront sensors

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Laser Guide Star (LGS) WaveFront Sensing faces a technological limitation in Shack Hartman concepts, due to the so-called spot elongation that leads to the need for very large detectors in order to accommodate the spot sampling on each SH sub-aperture.

Moreover, some trade-offs to minimize the number of pixels with either undersampling or truncation of the elongated SH-spots will induce non-linearity and bias effects which, through the propagation through the tomographic reconstruction process, will dramatically affect the final WFAO performance.

Innovative optical approaches can be proposed to significantly reduce the spot elongation before the physical detection by the CCD without any significant loss in flux nor performance. These approaches, based on free form optics and complex amplitude remapping techniques should allow obtaining a WFS design with 16 to 25 less pixels than the current ones and

thus making possible the use of already existing devices. It will also avoid the use of complex centroiding measurements making the whole WFS process simpler, faster and more robust.

This talk will show the recent advances on this activity undertaken at LAM-ONERA and STScI on 1/ optical design using Zemax and , 2/ opto-mechanical designs to accommodate the entrance beams and relay the flux to a 800x800pixels detector and 3/ estimation of performance, linearity and sensitivity of the compressed system in presence of aberrations.

9909-256, Session PWed2

Solving the MCAO partial illumination issue and laboratory results

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Telescopes or instruments equipped with Multi-Conjugated Adaptive Optics (MCAO) provide uniform turbulence correction over a wide Field of View (FoV), thereby overcoming the problem of isoplanatism and enabling previously impractical science. LINC-NIRVANA (LN), the German-Italian near-infrared high-resolution imager for the Large Binocular Telescope (LBT), has an advanced and unique MCAO module, which employs the Optical Co-addition of Layer-Oriented Multiple-FoV Natural Guide Star approach to MCAO using pyramid wavefront sensors. The layer-oriented approach conjugates the Deformable Mirrors (DM) and their respective Wavefront Sensors (WFS) to the corresponding atmospheric layers. LN corrects for the aberrations in two different layers. The ground layer, conjugated to the telescope pupil ~100m above LBT, is corrected by the Ground-layer Wavefront Sensors (GWS) driving the LBT adaptive secondary mirrors, and the High-layer Wavefront Sensors (HWS) drive a pair of Xinetics DMs on the LN bench to correct turbulence in a higher layer ~7.1km above the telescope.

In the WFS optically conjugated to the ground layer, the pupil footprints of the stars overlap completely and every star footprint illuminates the entire pupil-plane (corresponding to the FoV projection). However, for a higher layer conjugation, the footprints do not overlap completely and each star illuminates a different region of the FoV projection (also called as meta-pupil). Lack of stars, therefore, results in some regions not being illuminated, meaning no information regarding the turbulence in these areas. The optimum way of correcting the high layer, given this limited information, is the crux of the “partial illumination issue”. In this paper, we propose a solution for partial illumination and discuss laboratory results from the aligned LN bench in the lab at MPIA. Currently, LN is being re-integrated and re-aligned at LBT. We will test our algorithm in the final configuration at LBT in June 2016 with simulated stars during, and on sky in the second half of 2016.

9909-258, Session PWed2

Analytical expression of a long exposure coronagraphic point spread function and application to the estimation of quasi-static aberrations in the presence of residual turbulence with COFFEE

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The final performance of current and future instruments dedicated to exoplanet detection and characterization (such as SPHERE on the VLT, GPI on Gemini South or future instruments on the ELTs) is limited by intensity residuals in the scientific image plane, which originate in uncorrected optical aberrations. After correction of the atmospheric turbulence, the main contribution to these residuals comes from the quasi-static aberrations introduced upstream of the coronagraph which create long-lived speckles in the detector plane that can easily be mistaken for planets. In order to reach very high contrast such as the ones required to image earth-like planets, these aberrations need to be compensated for. We have recently proposed a dedicated focal-plane wave-font sensor called COFFEE (for COronagraphic Focal-plane wave-Front Estimation for Exoplanet detection), which consists in an extension of conventional phase diversity to a coronagraphic system: aberrations both upstream and downstream of the coronagraph are estimated using two coronagraphic focal-plane images, recorded from the scientific camera itself, without any differential aberration. Such a system has been successfully validated on the SPHERE instrument, where the phase reconstruction by COFFEE has been used to compensate for the phase aberrations upstream of the coronagraph, leading to a contrast optimization in the whole focal plane area controlled by the adaptive optics loop. The extremely high contrasts of the currently considered future missions dedicated to the direct imaging of terrestrial planets create the need to compensate for aberrations during the scientific observation itself. To this aim, the wave-front must be estimated on-sky, during the exposure. In order to address this issue, we propose in a first part an analytical expression giving the long-exposure optical transfer function of a coronagraphic system, while taking into account residual turbulence described by its phase structure function. We propose a first implementation of this formula under a form optimizing the computing time, mainly using fast Fourier transforms. The method is validated by comparison with a sum of short-exposure coronagraphic images. The second part consists in integrating this long-exposure analytical expression of the coronagraphic PSF into the COFFEE method in order to be able to estimate quasi-static aberrations on-sky in the presence of residual turbulence.

9909-259, Session PWed2

Efficient image shift measurement algorithms for extended scene Shack-Hartmann sensors

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Shack-Hartmann sensor extended scene slopes are usually evaluated with correlation algorithms. The evaluation involves two sub-computations: a) correlation estimation between a target and a reference. The peak of the correlation gives the image shift or slope in integer pixel precision; b) the sub-pixel precision image shifts are computed by applying a peak-finding algorithm to the correlation peak.

The estimated image shifts are usually affected by systematic errors due to pixel-locking or peak-locking effects. The nature of the systematic error is that the measured image shifts are concentrated at the closest integral pixel value. These are caused by under-sampling of the images. The magnitude of the systematic errors depends on the type of extended scene and the combination of correlation algorithm and peak-finding algorithm used. To reduce the systematic errors, several correlation and peak-finding algorithms are investigated in the field of feature tracking and strain measurement (Pan et al., 2009, Meas. Sci. Technol.). However, the real-time Shack-Hartmann wavefront sensing is significantly different from

their work. The Shack-Hartmann wavefront sensing is involved with: a) different types of images; b) images of small fields of view (for example, 16 x 16 pixels); c) real-time measurements.

In this study we approached the problem in three ways. Firstly, the performance of different correlation algorithms (cross-correlation; sum of squared differences; sum of absolute differences) is investigated for three classes of sub-aperture images (point source, elongated laser guide star, extended scenes). It is found that cross-correlation is most robust to the point source and elongated laser guide star. The sum of squared differences algorithm performances better (less failure rates) for extended scenes although it involves large systematic errors measurement.

Secondly, the performance study is extended to different peak-finding algorithms (parabola fit; threshold center of gravity; Gaussian fit; quadratic polynomial fit; pyramid fit) using the three classes of sub-aperture images. The study reveals that pyramid fit is preferable for extended scenes, while quadratic polynomial fit performs better for the elongated laser guide star. The threshold center of gravity performs better in a low SNR scenario cases, although the systematic errors in the measurements are large. It is found that no peak finding model is good enough in reducing both the systematic and the RMS centroid error.

Thirdly, a technique used in the fluid mechanics (Sjödahl 1994, App. Opt.) is applied here to overcome the above limitations. In this technique, the image sampling prior to the actual correlation matching is increased. The technique is realized in the image domain and is implemented in two steps to improve its computational efficiency: a) as a first step, the image shift is estimated by executing the cross-correlation algorithm at the original image sampling; b) next the cross-correlation is performed at a sub-pixel level spatial sampling by confining the correlation search to a small field of view (4 ? 4 pixels) centered at the position obtained in the first step.

Studies reveal that the image sampling improvement technique outperforms other first two approaches. It improves the image-shift measurement accuracy (wavefront sensing) by a factor of 5 in terms of both the systematic and the RMS errors, at the expense of twice the computational cost.

9909-260, Session PWed2

Experimental result from tip-tilt measurement with a laser guide star at Yunnan Observatories

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We report about an experiment aimed at verifying the statistical technique, which has been proposed first by Mikhail S. Belen'kii to solve the tilt indetermination problem from the laser guide star(LGS) adaptive optics system. The tilt components of wave fronts were measured synchronously from a Rayleigh guide star by use of a 0.25-m telescope as an auxiliary telescope and from a star by use of a telescope with a 1.2-m aperture at Yunnan Observatories. The auxiliary telescope was located 45m from the 1.2-m telescope. The jitter of the star is corrected by the tilt signal from auxiliary telescope by post processing. A transform function be used to keep corresponding relation between tilt measured from the LGS and the star. The average value of the measured cross-correlation coefficient between the tilt for the star and the LGS is 0.74 through one-night experiment. Those objective stars selected from different areas of sky. The result shows that the instability of the auxiliary telescope's tracking system is an important error source of the tilt measurement. A new idea for tip-tilt measurement will be also presented and discussed in the end of this paper.

9909-261, Session PWed2

Optical characterization of a glass pyramid for wavefront sensing: setup, procedures, and test results

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The use of a pyramid WFS for astronomical adaptive optics has been demonstrated on sky by the FLAO system at LBT. In the last years the astronomical community shown an increasing interest in the use of this type of WFS, expecially for high contrast applications. The key element of the WFS is a double-glass pyramid that allows to sample the wavefront derivative on a detector. The specifications for the manufacturing of such optical elements are challenging, expecially in the framework of the next generation of Extremely large telescopes.

This paper outlines on the impact of pyramid manufacturing errors on the wavefront measurement quality and it prensents a procedure to measure them in laboratory. It also describes a test setup that has been assebled in the Arcetri Observatory laboratory to characterize the GMT NGS WFS glass pyramid.

9909-262, Session PWed2

Correlation wave-front sensing of extended objects

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Most methods for wave-front sensing extended objects, whether they are elongated laser guide star images or solar granulation, require reference images. We present a method for creating reliable, super-sized reference images, using only wave-front sensor images. This can help mitigate some problems with truncation in laser guide star wave-front sensing, and part of the "expanding pupil problem" (where the extended field causes reduction in sensitivity to high altitude turbulence) in solar adaptive optics.

Generating a reference image requires the use of individual sub-aperture images, then aligning them in some way. This has the effect of averaging out noise found in the individual wave-front sensor images. The individual images are shifted with respect to each-other, so when a reference image is created there is information for a larger field of view than any of the individual sub-apertures. This information can be kept to make a super-sized reference image. This gives less truncation in laser guide star wave-front sensor images, and allows for smaller regions to be used in solar wave-front sensors, reducing the "expanding pupil" problem.

With both wave-front sensor images, and a reference image, it is possible to accurately estimate the optimal centroiding parameters for a centre of mass on the correlation images. Like the generation of the reference images this requires no external input, as the parameters can be estimated from noise statistics on the correlation images.

We present simulated results, for both laser guide star and solar wave-front sensing, where both centroiding parameters and reference images are calculated automatically, from a small number of wave-front sensor images. As there is no input, other than the wave-front sensor images, this process can be entirely automated, and done outside the adaptive optics system. This would allow for an adaptive optics system to run an artificially super-sized reference image with optimized centroiding parameters on a correlating wave-front sensor automatically, with no external inputs.

9909-264, Session PWed2

Development of an optical differential wavefront sensor based on binary pixelated transmission filters

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High-resolution, high-dynamic-range, and achromatic wavefront sensing is highly desired for astronomical imaging and metrology applications. Particular domains of interest include wavefront sensing of broadband sources, fast low-order sensors for real-time turbulence compensation, and characterization of highly aspherical optics and freeform optics used in imaging systems.

An optical differentiation wavefront sensor (ODWS) relies on an optical system that images the pupil to a camera. A filter with a linear amplitude-transmission gradient is located in a far field of the pupil. The fluence measured in the detection plane is linked to the input wavefront slope in the direction of the focal-plane transmission gradient. The ODWS uses the data measured in the detection plane for two orthogonal orientations of the focal-plane filter to determine wavefront-slope data along the two corresponding directions in the pupil plane. The wavefront in that plane can be reconstructed from the data via reconstruction algorithms used for other wavefront-sensing techniques measuring wavefront slopes data, for example Shack-Hartmann wavefront sensors.

Although potentially advantageous, the ODWS is not commonly used and is not commercially available, which can be attributed to the difficulty of manufacturing optical components with well-controlled spatially varying transmission. We investigate the performance of an ODWS relying on binary pixelated transmission filters. Such filters can be fabricated with high accuracy using conventional metal-on-glass lithography techniques and have been used for laser beam shaping and coronagraphy. A spatially dithered distribution of transparent and opaque pixels can synthesize a continuously varying transmission filter, a process analogous to gray-level rendition with black-and-white printing and display systems.

When the pixels of the binary filter are small enough, the noise due to pixelation and binarization is rejected at high frequencies that do not impact the performance. We numerically investigate how the resulting noise in the detection plane impacts the performance of an ODWS based on binary pixelated filters for different wavefront profiles, pixel sizes, and diagnostic parameters. This performance is compared to the performance of an ODWS implemented with an ideal continuous filter. An ODWS implemented with a binary pixelated filter having 10-micron pixels is experimentally demonstrated. The diagnostic is able to reconstruct various wavefront profiles and yields self-consistent results that are in good agreement with a commercial Shack-Hartmann sensor.

The following conceptual and practical advantages assert the relevance of the ODWS to the current and future astronomical needs: (1) The potential high-resolution and large dynamic range is relevant to the characterization of large optics and large phase gradients, which are challenging for interferometers and Shack-Hartmann sensors. (2) The implementation without refractive components reduces the chromaticity of this sensor, an advantage for wavefront sensing of polychromatic sources. (3) Acquisition in real-time and without moving parts eliminates the requirement for continuous dithering of the pyramid-apex position or use of a deformable mirror for phase diversity. (4) Commercially available binary pixelated filters, with metal-on-glass lithography techniques allow custom substrates, metal layers, and coatings for addressing different needs.

9909-265, Session PWed2

ZELDA: a Zernike sensor for near-coronagraph quasi-static measurements: concept studies and results with VLT/SPHERE

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The high-contrast imaging instruments VLT/SPHERE and GPI have been routinely observing gas giant planets, brown dwarfs, and debris disks around nearby stars since 2013-2014. In these facilities, low-wind effects or differential aberrations between the extreme Adaptive Optics sensing path and the science path represent critical limitations for the observation of exoplanets orbiting their host star with a contrast ratio larger than 1e6 at small separations. To circumvent this problem, we proposed ZELDA, a Zernike wavefront sensor to measure these quasi-static aberrations at a nanometric level. A prototype was installed on VLT/SPHERE during its integration in Chile. We recently performed measurements on an internal source with ZELDA in the presence of Zernike or Fourier modes introduced with the deformable mirror of the instrument. In this communication, we present the results of our experiment and report on the contrast gain obtained with a first ZELDA-based wavefront correction. We finally discuss the suitability of such a solution for a possible upgrade of VLT/SPHERE and for its use with future E-ELT instruments or space missions with high-contrast capabilities (e.g. WFIRST-AFTA, HDST).

9909-266, Session PWed2

Characterising latency for AO optical sensors: an implementation

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Adaptive Optics are a series of optical techniques utilized to mitigate atmospheric distortion of telescope measurements by performing high-speed environmental measurements and applying pre or post correction to certain optical systems. As can be easily surmised, the latency of cameras in an AO system; the time between end-of-exposure and the corresponding data becoming available, is a critical parameter to be considered. However, this value is not one commonly published by camera manufacturers.

This paper describes the methodology and preliminary results of a technique used to characterise the latency of optical devices. The purposes of this characterisation are twofold; to supplement manufacturer data for COTS cameras , allowing for a more complete cost-benefit analysis, and to improve the characterisation of the AO system as a whole.

In this methodology, pulses generated by an optical chopper are received by the camera. The duration and frequency of these pulses are controlled by manufacture of custom chopper wheels; the frequency (usually about one tenth of the camera sample rate) is altered to ensure that each pulse is distinct, and duration kept small (relative to exposure time) to allow the pulse to be timed to the end of exposure. Exposed frames are then retrieved through software and evaluated for delay, using a reference

signal from the pulse generator that serves as a time stamp.

In order to limit the influence of equipment on the latency measurement, low level software and simple analogue electronics are used wherever possible. Pulses and frames are synchronized using a serial interface implemented in C within a Linux environment; during the alignment phase, a control loop adjusts the timing of the pulse towards the end of a single frame by steadily increasing the phase of the system until a single pulse 'bleeds' into two exposures, and then reversing the most recent change. Reference signals are generated by splitting the pulse and directing one split through a high-speed photodiode into a battery powered serial converter, effectively an Analogue-Digital Converter with two states. This converter uses transistors and bias currents in a typical push-pull configuration to create a digital switch tuned to the voltage output of the photodiode.

A simpler methodology is also proposed and discussed, wherin an LED is driven from a serial port and pulsed. The timestamp of the pulse command and frame retrieval are compared to allow the computation of latency. Due to the non-linear rise and fall times of the LEDs (characterised as part of this process), optimization of pulse length and intensity is performed to develop the most optimal signal-to-noise ratio.

9909-267, Session PWed2

Low photon-count tip-tilt sensor

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Due to the low photon-count of dark areas of the universe, signal strength of tip-tilt sensors is low, limiting sky-coverage of reliable measurements. Tip-tilt is the most prominent aberration in astronomical observations, causing motion blur due to movement of the observed object on the detector for long shutter times. These take 80% of the aberrations for 2.2 m diameter telescopes, and more if the telescope diameter decreases to Frieds parameter. Although tip-tilt can be corrected by a tip-tilt mirror using a natural guide-star or an on-CCD tip-tilt image compensator, sky coverage is limited due to the low photon count of dark areas of the universe. For aberrations other than tilt, adaptive optics (AO) systems use artificial guide stars to achieve proficient wavefront sensor signal. These systems cannot determine absolute tilt, due to wandering of the artificial guide star.

Measuring tip-tilt is usually done using a four quadrant detector (4QD), or image detectors. 4QDs have are fast and have good resolution, but are limited in linear range, have beam shape dependency, need regular calibration, and can only measure one target at a time. Therefore, many tip-tilt detector implementations divide image detectors in 4 sections to form 4QDs, offering high sensitivity, large linear range, and tracking multiple targets at once. For fast readout, detectors make use of high speed cameras combined with fast processing hardware, such as field programmable gate arrays (FPGAs). To improve quantum efficiency, single photon detectors and single photon cameras are applied, using the photo-avalanche effect.

As the signal strength of detectors is fundamentally limited by their photon-count, this paper present the conceptual design of the low photon-count tip-tilt (LPC-TT) sensor to improve the photon count of tip-tilt detector segments by its optical design. This improvement is realized by spatially sampling the image plane, overlaying these samples and summing these up to an integral image, as done in illumination systems to achieve uniform illumination, also known as field compression. Lab experiments show this sampling and integration aspect and also the ability to measure tip-tilt.

As such, the probability that two individual sources coincide on a detector segment increases. The increased probability of more photons on a segment potentially could improve the signal to noise ratio (SNR). Numerical simulations show an improved detector SNR of about 10dB compared to conventional tip-tilt sensors. This enables the LPC-TT to measure tip-tilt of darker scenes to increase sky-coverage, or decrease shutter time to increase the sampling rate to achieve higher bandwidth of tip-tilt correction.

9909-268, Session PWed2

Fast gradient-based algorithm on extended landscapes for wavefront reconstruction of Earth observation satellite

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For future Earth observation missions, CNES plans to use systems with optical aberrations, these aberrations being measured and compensated with an active loop. In this framework, a Shack-Hartmann wave-front sensor could be used on extended scenes (landscapes). A wave-front computation algorithm should then be implemented on-board the satellite to provide to the control loop wave-front error measure. In the worst case scenario, this measure should be computed before each image acquisition. A robust and fast shift estimation algorithm between Shack-Hartmann images is then needed to fulfill this last requirement. A fast gradient-based algorithm using optical flows with a Lucas-Kanade method has been studied and implemented on an electronic device developed by CNES. This electronic device uses qualified radiations-hardened components designed for space applications. The algorithm has been simplified compared to a reference software (floating-point) which uses iterative optical flow estimation to reach the final shift measurement with image resampling between two iterations. The implemented version of the algorithm uses only two iterations and gives results comparable to the reference software ones in terms of wave-front error assessment. Furthermore, pre-processing steps such as radiometric harmonization and image aliasing reducing have been implemented. Radiometric harmonization is mandatory when computing optical flows between partially occulted and non-occulted lenslets. Image aliasing has to be reduced to correctly estimate shifts between two images. Finally not only shifts are calculated between a reference image of the Shack-Hartmann and all the others but also the wave-front estimation using Zernike polynomials is performed on the board. This board is composed of an FPGA (ATF280) and a GR712 composed of two LEON3 processors running at 80MHz. The embedded RAM is 256Mbytes. Both pre-processing and post-processing (WFE estimation from shifts between images) steps are executed in the software part of the board (LEON3), the optical flows between Shack-Hartmann images being realized in the hardware part. Optical flows algorithm is well-suited for a hardware implementation because it uses image gradients and image differences computation. Pre-processing and shift estimation processing times are satisfying for on-board applications. For the Shack-Hartmann sensor considered by CNES, these processing times are around 250ms. Performances have been compared to the reference software on an exhaustive benchmark with different input wave-front errors, different landscapes and several radiometric conditions. Some landscapes are disadvantageous for shift estimation because of low signal to noise ratio or because of a main direction in the image (road, coasts...). Selection of favorable landscapes opposed to bad ones can be performed with selection criteria which are computed during the optical flow (Cramer-Rao Lower Bound and eigenvalues of the Fisher Information Matrix). These criteria have also been implemented recently on the electronic board and lead to higher number of landscapes processed in the same time as without selection criteria. Indeed, the board interrupts its processing when the criteria are under a threshold determined over the exhaustive benchmark and goes to the next landscape. In further studies, CNES could use this board to implement other algorithms such as phase diversity on extended landscapes.

9909-269, Session PWed2

The pyramid wavefront sensor used in the closed-loop adaptive optics system

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Pyramid wavefront sensor is a promising sensor technology based on the beam splitting in the focal plane. Due to its advantages of adjustable gain and variable spatial sampling, the pyramid wavefront sensor has been successfully applied in many large telescopes. In recent years, we have carried out the related research of this sensor. Firstly we studied the adaptive optical closed-loop system based on the liquid crystal spatial light modulator and the pyramid wavefront sensor, and then the system used the deformable mirror is also studied. Subsequently, the experiment on the 1.8-m telescope at Yunnan observatory has been successfully carried out and the high resolution images of the natural stellar star have been obtained. Currently the adaptive optical system based on the pyramid wavefront sensor with variable subaperture sampling is studied and different mode-restoration algorithm is analyzed in our lab. The latest observation experiments results are present in this paper.

9909-47, Session 13

Astronomical AO in Key Laboratory of Adaptive Optics, Chinese Academy of Sciences *(Invited Paper)*

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The AO progresses for astronomy in the Key Laboratory of Adaptive Optics, Chinese Academy of Sciences are reported in this presentation. For night-time astronomical observations, the recent AO technological developments, such as Laser Guide Star, Pyramid Sensor and Deformable Secondary Mirror, are introduced. The solar AO researches are also presented for day-time astronomical observations. Furthermore, we will show the on-sky high resolution observational results in the 1.8m telescope at Gaomeigu site, Yunnan Observatory and the 1-m New Vacuum Solar Telescope (NVST) at Fuxian Lake Solar Observatory respectively.

9909-48, Session 13

Robo-AO Kitt Peak: status of the system and optimizing the sensitivity of a sub-electron readnoise IR camera to detect low-mass companions

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Robo-AO KP is an autonomous laser guide star, adaptive optics (AO) instrument now deployed on the 2.1-m telescope at Kitt Peak, Arizona. It will be the only instrument on the telescope at Kitt Peak for the next three years and a portion of time will be made available to the wider astronomy community through NOAO. The system is based on a reconfiguration of the Robo-AO prototype that operated on the 1.5-m telescope at Palomar, California. Robo-AO has the unique ability to observe up to 250 targets in one night at the visible diffraction limit, ~0.1".

The addition of an infrared camera to Robo-AO KP will allow us to widen the scope of possible targets – specifically to much redder and low-mass objects, and to conduct the largest ever AO surveys in the infrared. The camera will double as an IR science detector and as a tip-tilt sensor that takes advantage of significant image sharpening in the infrared. The IR camera uses brand new infrared avalanche photodiode array technology (SAPHIRA detector), which has so far only been used for fringe tracking, demonstration tests, and with the prototype Robo-AO system on a limited basis in 2014. This will be the first long-term deployment of such a camera on an adaptive optics system for science applications.

We present the current status and performance of the system and describe the optimizations and calibrations performed since its deployment to Kitt Peak in November 2015, which we compare to its performance at Palomar. Such optimizations and calibrations include: creating and testing quad-cell response look-up-tables (for calibrations and on-sky observations), comparing a UV LED with narrowband filter to a 355nm laser with a fiber mode-scrambler used for minimizing non-common path optical errors from the wavefront sensor to the science camera, determining the optimal height in the atmosphere where the laser wavefront focus is located (laser range gate) and depth (measurement error), determining the optimal gain settings for each controlled basis function of the adaptive optics control loop to minimize residual wavefront sensor errors, and calibrating non-common path errors during on-sky operations by determining the required slope offsets with an auxiliary low-bandwidth wavefront sensor.

We will also present our near-future plans for Robo-AO at Kitt Peak, including optimizations such as deriving and testing new reconstruction matrices for the deformable mirror response to the wavefront sensor. The optimizations and commissioning of the camera happen in parallel with science observing programs.

9909-49, Session 13

The ERIS adaptive optics system

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The Enhanced Resolution Imager and Spectrograph (ERIS) is the new Adaptive Optics (AO) instrument for the VLT aiming to replace NACO and SINFONI. Its development is led by a Consortium of Max-Planck Institut fuer Extraterrestrische Physik, UK Astronomy Technology Centre, ETH Zurich, European Southern Observatory (ESO) and Istituto Nazionale di Astrofisica (INAF). ERIS will host a new high-resolution camera (NIX) ranging from 1 to 5 microns and SPIFFIER, a refurbishment of the Integral Field Unit spectrograph currently installed in SINFONI, covering J, H and K bands. ERIS will be installed at the Cassegrain focus of the VLT UT4, which is also hosting the Adaptive Optics Facility (AOF). The ERIS AO system is developed by INAF, with ESO's collaboration, and provides a Natural Guide Star (NGS) mode to deliver high contrast correction and a Laser Guide Star (LGS) mode to extend high Strehl performance to large sky coverage, enabling observations from exoplanets to high redshift galaxies.

The science and AO beams are split by an IR/VIS dichroic. The SPIFFIER and NIX instruments are in the transmitted beam with a retractable selector mirror for feeding NIX. The ERIS AO module is fed by the reflected beam and provides single conjugate correction using two different wavefront sensors (WFS). The high order LGS WFS is a 40x40 sub-aperture Shack-Hartmann (SH) that is coupled with the standard AOF WFS camera integrating an electro-magnified CCD220 detector. The visible

(<1um) NGS WFS, also coupled with CCD220 camera, has a baseline SH design with a switchable configuration between 40x40 sub-apertures, for stand-alone NGS AO mode, and 2x2 sub-apertures, providing the tip-tilt and focus sensing to support the LGS mode observations. A possible upgrade of the NGS WFS to a Pyramid WFS is also presented, pushing the performance to higher levels of contrast and Strehl ratio. ERIS AO uses the 1170-actuator Deformable Secondary Mirror (DSM) as wavefront corrector and one of the Sodium Laser Launchers of the 4 Laser Guide Star Facility (4LGSF) of AOF. The ERIS AO module real-time computer is based on the ESO's SPARTA platform customized for the specific needs of ERIS. The use of a deformable mirror that is external to the AO module allows to design an optical relay using low-power optics to keep stable non-common-path aberrations and with reduced optical sensitivity to flexures. The WFS units are implemented as ~500x500mm optical boards supported by stages to track the focus and, in the case of the NGS WFS, to patrol the acquisition field (1 arcminute radius).

In this paper we introduce the concept of the ERIS AO module by describing its opto-mechanical design, providing an overview of the overall control strategy and, finally, presenting the estimated correction performance.

9909-50, Session 13

Status of the GTC adaptive optics program

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An Adaptive Optics (AO) system was considered necessary since the beginning of the development of the Gran Telescopio Canarias (GTC), in order to exploit the full diffraction-limited potential of the telescope. The AO system designed in the last years is based on a single deformable mirror conjugated to the telescope pupil, and a Shack-Hartmann wavefront sensor with 20 x 20 subapertures, based on an OCAM2 camera. The GTCAO system will provide a corrected beam with a SR of 0.65 in K-band with bright natural guide stars.

Most of the subsystems have been manufactured and delivered. The present status of the GTCAO system, currently in its laboratory integration phase, is summarized in this paper. The upgrade for the operation with a Laser Guide Star (LGS) system has been approved, and the conceptual design of the Laser Guide Star Facility is also presented, together with its first performance analysis.

9909-51, Session 13

First light of the deformable secondary mirror-based adaptive optics system on 1.8m telescope

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An adaptive optics system (AOS), which consists of a 73-element piezoelectric deformable secondary mirror (DSM), a 9x9 Shack-Hartmann wavefront sensor (SHWFS) and a real time controller has been integrated on the 1.8m telescope at the Gaomeigu site of Yunnan Astronomical Observatory, Chinese Academy of Sciences. The vertex curvature and eccentricity of the DSM's reflecting surface are compatible with the Nasmyth focus of the 1.8m telescope. To release the requirements on the DSM and SHWFS, a tracking subsystem is introduced. The tracking subsystem consists of a tracking sensor, a processor and a fast steering mirror. Compared to the traditional AOS on the Coude focus, the DSM based AOS adopts much less reflections and consequently restrains the thermal noise and increases the energy transmitting to the system. Before the first on-sky test, this system has been demonstrated in the laboratory by compensating the simulated atmospheric turbulence generated by a rotating phase screen. The test of the convex hyperboloid surface of the DSM is a problem during the laboratory demonstration. A testbed origin from the Simpson-Oland-Meckel method is proposed and a Hindle element with a concave surface is fabricated. The system calibration procedures including the optical registration and the interaction matrix acquisition are very important for the DSM based AOS to reach the performance specifications of the design. Thus the pupil shift, rotation as well as the magnification are adjusted by measuring the SHWFS responses for the specific actuator patterns applied on the DSM. In order to reject the atmospheric turbulence during the on-sky measurement of the DSM based AOS interaction matrix, a new multichannel-modulation calibration method is proposed and verified by closed-loop experiments. The laboratory characterization and performances of the system are reported. After integration on the 1.8m telescope, the on-sky calibration of the DSM based AOS is validated. The closed-loop compensation of the atmospheric turbulence with the DSM based AOS is achieved afterwards, and the first light results from the on-sky experiments are reported.

9909-52, Session 14

Review of adaptive optics in the visible *(Invited Paper)*

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I will review astronomical results in the visible (<1micron) with adaptive optics. Other than a brief period in the early 1990s, there has been little astronomical science done in the visible with Adaptive Optics until the last 3 years. Visible AO has been key to thousands of observed targets with robotic AO with the Robo-AO system now installed at the Kitt Peak 2m telescope. The largest telescope with visible AO is the VLT's Sphere/Zimpol, which has made excellent polarized light maps of circumstellar disks. The most productive large telescope visible AO system at the bluest wavelengths (~0.6microns) to date is the 6.5m Magellan telescope AO system (MagAO). MagAO is an advanced Adaptive Secondary AO system at the Magellan 6.5m in Chile. This secondary has 585 actuators with < 1 msec response times (0.7 ms typically). We use a pyramid wavefront sensor. The relatively small actuator pitch (~23 cm/subap) allows moderate Strehls to be obtained in the visible (0.63-1.05 microns). MagAO uses a CCD AO science camera called "VisAO". On-sky long exposures (60s) achieve 20-30 mas resolutions, 30% Strehls at 0.62 microns (r') with the VisAO camera in 0.5" seeing with bright R < 9 mag stars, whereas with fainter R~12 mag MagAO still enables ~40mas images at H-alpha. These relatively high visible wavelength Strehls are made possible by our powerful combination of a next generation ASM and a Pyramid WFS with 378 controlled modes and 1000 Hz loop frequency. We'll review the key steps to having good performance in the visible and review the exciting new AO visible science opportunities and refereed publications in both broad-band (r,i,z,Y) and at H-alpha for accreting exoplanets (for the first time), protoplanetary disks, young stars, and emission line jets. These examples highlight the growing power of visible AO to probe circumstellar regions/spatial resolutions that would otherwise require much larger diameter (D>15m) telescopes with classical infrared (1.6 micron) AO cameras.

9909-53, Session 14

Astrometry with adaptive optics *(Invited Paper)*

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The high spatial resolution delivered by adaptive optics provides large gains in relative astrometry and proper motions. Currently, AO astrometry can reach precisions of 0.15 milli-arcseconds (mas) in crowded fields and <1 mas in sparse fields. I will review science results that have most benefitted from precision AO astrometry in areas. Some examples include the discovery of the supermassive black hole at the Galactic Center, constraining orbits of exoplanets, measurement of the structure, dynamics, and initial mass function in massive young star clusters throughout the Milky Way, testing stellar evolution models with multiple star systems, and a search for free-floating stellar mass black holes. I will also present a number a future science cases where precision AO astrometry, both in crowded and sparse fields, is essential.

Additionally, I will discuss some of the technical lessons learned and how existing and future AO systems can be improved to deliver precision astrometry. For instance, one main limitation in single-conjugate AO systems is knowledge of the point spread function (PSF) both on and off-axis. Furthermore, AO system stability is essential and flexure or thermal variations can limit their capacity to reach below 1 mas. I will review the careful calibration programs and on-sky tests that are needed to validate if an existing AO system can deliver precise astrometry. In crowded fields, careful image transformation algorithms are needed to maximize astrometric precision. Finally, I will discuss astrometric capabilities on future AO systems, including on the E-ELTs, and how astrometric requirements are driving some design choices.

9909-54, Session 14

High-precision astrometry towards ELTs

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Accurate astrometry will be one of the major benefits of a diffraction limited Extremely Large Telescope (ELT). The goal of the Multi-AO Imaging Camera for Deep Observations (MICADO), one of the first light instruments for the European-ELT is a relative astrometric accuracy of 50 microarcsec. In order to reach such an ambitious goal, a dual approach is necessary. Firstly to simulate stellar fields with the predicted instrumental PSF and analyse the resulting realistic images to test the predicted performance, and to help optimise the instrumental design. Secondly, present-day astrometric studies with existing Multi-Conjugate Adaptive Optics (MCAO) facilities are crucial to test the main sources of inaccuracy not purely related to the instrumental design or telescope. In this paper we present both these approaches. In particular, we investigate how to best reach the astrometric requirement for MICADO by quantifying the errors associated to the major components in the light path. This investigation is carried out making simulations with the Single Conjugate module PSF in the central region of a crowded globular cluster, with an assumed field of view of $approx 10 times 10$ arcsec.

We will also present the results of an astrometric study performed with Gemini Multi-Conjugate Adaptive Optics System (GeMS) observations of the Galactic globular cluster NGC6681. This cluster is the most centrally concentrated in the Galaxy, and thus represents a major observational challenge in terms of stellar crowding. We have previously determined proper motions from comparing two Hubble Space Telescope epochs (Massari et al. 2013). Thus this cluster is the ideal candidate to test the effects that may be introduced by MCAO corrections on proper motion measurements and related uncertainties. In particular, we looked for systematics introduced by the GeMS geometric distortions by: observing through both J and Ks filters; investigating the effect of the shape of the Natural Guide Star constellation configuration and finally the effects of the reduction software used. Our investigation is the first to address the accuracy of proper motion measurements over a temporal baseline of several years with any MCAO instrument in direct comparison with HST, and will therefore be the starting point for understanding MCAO astrometry capabilities and any future improvements in the calibration requirements and data reduction strategy for ELT observations.

9909-55, Session 15

Solar adaptive optics: specificities, lessons learned, and open alternatives

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First on sky adaptive optics experiments were performed on the Dunn Solar Telescope on 1979, with a shearing interferometer and limited success. Those early solar AO efforts forced to custom-develop many components, such as DMs and WFSs, which were not available at that time. Later on, the development of the correlation Shack-Hartmann marked a breakthrough in solar AO. Since then, successful Single Conjugate AO instruments have been developed for many solar telescopes, i.e. the National Solar Observatory, the Vacuum Tower Telescope and the Swedish Solar Telescope. Success with the Multi Conjugate AO systems for GREGOR and the Big Bear Solar Telescope have proved to be more difficult to attain. Such systems have a complexity not only related to the degrees of freedom, but also related to the specificities of the Sun, used as reference, and the sensing method. The wavefront sensing is performed using correlations on images with a field of view of ~10", averaging wavefront information from different sky directions, affecting the sensing and sampling of high altitude turbulence. Also due to the typical elevation at which solar observations are performed we have to include generalised fitting error and anisoplanatism, as described by Ragazzoni and Rigaut, as non-negligible error sources in the MCAO error budget. For the development of the next generation MCAO systems for the Daniel K. Inouye Solar Telescope and the European Solar Telescope we still need to study and understand these issues, to predict realistically the quality of the achievable reconstruction. To improve their designs other open issues have to be assessed, i.e. possible alternative sensing methods to avoid the intrinsic anisoplanatism of the wide field correlation Shack-Hartmann, new parameters to define the performance of an AO solar system, alternatives to the Strehl and the PSF used in night time AO but not really suitable to the solar systems, and new control strategies more complex than the ones used in nowadays solar MCAO systems. In this paper we summarize the lessons learned with past and current solar AO systems and focus on the

discussion on the new alternatives to solve present open issues limiting their performance.

9909-56, Session 15

Adaptive optics for MOSAIC: design and performance of the wide(st)-field AO system for the E-ELT

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MOSAIC is the proposed multiple-object spectrograph for the E-ELT that will utilise the widest possible field of view provided by the telescope. In terms of adaptive optics, there are two distinct operating modes required to meet the top-level science requirements. The MOSAIC High Multiplex Mode (HMM) requires either seeing-limited or GLAO correction within a 0.6" (NIR) and 0.9" (VIS) subfields over the widest possible field for a few hundred objects. To achieve seeing limited operation whilst maintaining the maximum unvignetted field of view for scientific observation will require recreating some of the functionality present in the Pre-Focal Station relating to control of the E-ELT active optics.

MOSAIC High Definition Mode Control (HDM) requires a 25% encircled energy within 150mas in the H-band element for approximately 10 targets distributed across the full E-ELT field, implying the use of MOAO. Initial studies have shown that to meet the encircled energy requirements whilst maintaining high-sky coverage will require the combination of wavefront signals from both high-order NGS and LGS to provide a tomographic estimate for the correction to be applied to the open-loop MOAO DMs.

In this paper we present the current MOSAIC AO design and provide the first performance estimates for the baseline instrument design. We then report on the various trade-offs that will be investigated throughout the course of the Phase A study, such as the requirement to mix NGS and LGS signals tomographically. Finally, we discuss how these will impact the AO architecture, the MOSAIC design and ultimately the scientific performance of this wide-field workhorse instrument at the E-ELT.

9909-57, Session 15

Testing the pyramid truth wavefront sensor for NFIRAOS in the lab

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NFIRAOS (Narrow Field InfraRed Adaptive Optics System) is a first light adaptive optics (AO) system for Thirty Meter Telescope (TMT). It is a multi-conjugate AO system equipped with six laser guide stars (LGSs), two deformable mirrors (DMs), and a natural guide star (NGS) pyramid wavefront sensor (PWFS). The advantage of the PWFS over the conventional Shack-Hartmann Wavefront Sensor (SHWFS) is its greater sensitivity and dynamic range tuned by modulation amplitude. In NFIRAOS, the PWFS will be used as a high-order wavefront sensor when LGSs are off, and as a truth wavefront sensor (TWFS) when LGSs are on. The TWFS provides improvements over conventional AO systems by monitoring the slowly varying sodium layer profile and measuring radial wavefront errors due to these profile variations. The performance of our TWFS is therefore critical to NFIRAOS, which we test using our Herzberg NFIRAOS Optical Simulator (HeNOS) bench.

The HeNOS bench at NRC Herzberg is a scaled-down version of NFIRAOS with four LGSs, a grid of NGSs, two DMs, three turbulence screens, a SHWFS, and a science camera to simulate NFIRAOS performance in the laboratory bench. Due to the number of actuators (n=9) on the ground layer DM (DM0), the bench is equivalent to an 8-m telescope rather than a 30-m. However, we scaled the bench so that our science field of view matches with the same number of anisoplanatic angles as in NFIRAOS.

In this paper, we describe the design and the lab testing results of the newly added TWFS on HeNOS bench. Due to the space and capability of HeNOS bench in the lab, the HeNOS-TWFS is used to measure tip/tilt/defocus in addition to the simulated sodium layer profile. Our TWFS path consists of a star selection mirror (SM), a pinhole, a modulation mirror (MM), a focusing lens, a microlens array in the focal plane as a pyramid, a relay lens, and a CCD detector. Both the SM and MM are conjugated to the pupil located at DM0. The grid of NGSs is separated by 0.4", where 21 NGSs are on one axis, and the SM is able to position one NGS at the center of the pinhole at a time. The MM has the resolution and range to modulate the amplitude from r = 3?/D to 40?/D. We apply defocus to DM0 and make LGS spots on SHWFS elongated while modulating the LGS spots' intensity to simulate the time varying sodium layer profile.

9909-270, Session PThu1

Daytime turbulence profiling for EST and its impact in the solar MCAO system design

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An intensive site-testing campaign has been carried out by the IAC during the last years in order to characterize the daytime turbulence for the two candidate sites for the construction of the European Solar Telescope: the Observatorio del Teide (OT) in Tenerife and the Observatorio del Roque de los Muchachos (ORM) in La Palma. The main collected data consist in low height (reliable up to 2Km approximately) daytime turbulence profiles. The instrument used for acquiring the data needed to calculate those profiles is the Long Baseline Shadow Band Ranging (SHABAR). One of the objectives of this turbulence characterization campaign is the selection of the most appropriate site for building the telescope, with simultaneous observation in both observatories. Tests for ensuring the comparability of the profiles generated by the two simultaneously-working SHABARs have been performed. Tests for checking the correctness of the generated profiles where also performed by observing with both instruments in the same site at the same and different heights.

SHABAR data was calibrated with the aid of data coming from a different instrument (a Wide Field Wavefront Sensor WFWS) installed at the Swedish Solar Tower (SST), in La Palma, where one of IAC SHABARs is located. The WFWS estimates the Fried's parameter at the telescope entrance, which is useful for calibration. Data from a shorter SHABAR operated at the SST, calculating turbulence profiles for smaller heights (up to 300m approx.), was also available and used for calibration and validation of our data.

Once our data was totally calibrated and cleaned, different statistics and average profiles were calculated. Average profiles for different seasons and hours of the day, using solar noon as a reference, were calculated. All these low height profiles needed to be aggregated with the higher height profiles available from the nighttime turbulence. We work with the assumption that the ground turbulent layer is more affected by sunlight, due to convection caused by ground heating, while higher altitude layers are more stable and its behavior could be considered to be similar during night and day.

The resulting turbulence profiles covering the full important height range serve as input for software simulations for the MCAO telescope design. The objective of these simulations is finding the best number of deformable mirrors to include in the MCAO system and their positions.

This paper presents the architecture and working principle of the Long Baseline SHABAR instrument, explains the different tests that were held for validation and for calibration with SST data, explains how the low height turbulence data was cleaned, how the profiles were aggregated in order to obtain average profiles, how those profiles are fused with higher altitude turbulence profiles coming from the night turbulence data, explains the software simulations performed and how the profiles are essential inputs for calculating the most appropriate number and position of mirrors, taking into account a set of relevant variables.

9909-273, Session PThu1

Ultimate limitations of tomographic reconstruction for WFAO systems on E-ELT

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WFAO systems are now the baseline of any E-ELT's AO system. LTAO, MCAO and MOAO (in order of complexity) approaches are essential to achieve the ultimate scientific return of first light and first generation of ELT's instrumentation. All these AO systems require a precise tomographic reconstruction of the turbulent volume. They are all going to use multiple Laser and natural guide stars wave-front sensing strategies to retrieve the 3D information of the atmospheric turbulence. In that frame, guide stars (Laser and Natural) asterisms and Cn2 profiles (coming up at two levels: the input "true" profile, and the prior profile used as a regularization in the tomographic reconstruction) are the fundamental ingredients of the reconstruction processes. We show that isoplanatic angle is not sufficient to characterize profiles in WFAO. The impacts of the structure and the complexity of the Cn2 profile on the residual error after tomographic reconstruction are analyzed and discussed. We highlight the importance of a well sampled Cn2 input profile and prior profile to be considered in the tomographic reconstructor and we draw some simple and yet essential engineering rules between the size of the technical FoV (3D area on which the turbulence has to be reconstructed), the number of measurements and the Cn? structures. Implications on the design and the performance of WFAO systems (LTAO, MCAO and MOAO) for the E-ELT are derived.

9909-277, Session PThu1

Comparison between simulations and lab results on the ASSIST test-bench for the AOF

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In this poster, we will present the latest comparison results between lab test carried out on the ASSIST test bench (for the ESO Adaptive Optics Facility, AOF) and Octopus end-to-end simulations. We simulated, as closely to the lab conditions as possible, the different AOF modes (Maintenance and commissioning mode (SCAO), GRAAL (GLAO in the near IR), Galacsi Wide Field mode (GLAO in the visible) and Galacsi narrow field mode (LTAO in the visible)). We then compared the simulation results to the ones obtained on the lab bench. Several aspects were investigated, like number of corrected modes, turbulence wind screens, LGS photon flux etc. The agreement between simulations and lab is remarkably good for all investigated parameters, giving great confidence in both simulation tool and performance of the AO system in the lab.

9909-280, Session PThu1

MICADO SCAO numerical simulations

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MICADO is the E-ELT first light imager, working at the diffraction limit in the near infrared. Optimized to work with the MAORY Multi-Conjugate Adaptive Optics (MCAO) module, MICADO will also come with a single conjugate adaptive optics (SCAO) capability motivated by scientific programs for which SCAO will deliver the best AO performance (e.g. exoplanets, solar system science, bright AGNs, etc).

This SCAO capability will be developed within MICADO through a dedicated SCAO module with its natural guide star (NGS) wavefront sensor (WFS), allowing MICADO to work in SCAO stand alone mode without MAORY, and inside MAORY with the same dedicated NGS WFS. Currently Shack-Hartmann (SH) or pyramid WFS are both envisioned for the wavefront measurement of the SCAO mode. In addition to WFS design considerations, numerical simulations are therefore needed to trade-off between these two WFS.

COMPASS (COMputing Platform for Adaptive optics SyStems) is a GPU-based adaptive optics end-to-end simulation platform allowing us to perform numerical simulations in various modes (SCAO, LTAO, MOAO, MCAO...). COMPASS was originally bound to Yorick for its user interface and a major upgrade has been recently done to now bind to Python allowing a better long term support to the community.

We first present the specific developments performed to achieve a fast and accurate E-ELT scale simulation (E-ELT pupil, spiders, M4 geometry and influence functions, segment cophasing error, pupil rotation...). We then present the latest simulations results performed in the framework of the MICADO SCAO study. Thanks to the speed of computation of COMPASS we are able to span quickly a very large parameters of space at the E-ELT scale. We present the results of the first study between WFS choice (SH or pyramid), WFS parameters (noise, number of subapertures, pixel scales...), turbulence parameters (including Cn2 profiles, r0 and L0 variations), and AO controls (frequency, loop gains...). Finally we try to build a first error budget comparison on some specific cases and conclude on the expected performance. These results will pave the way of work for the future developments for the SCAO of MICADO.

9909-282, Session PThu1

Status update and long term development plan for the COMPASS simulation platform

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Monte Carlo simulations called end-to-end are widely used in the community of instrumentation to predict system performance, to test new concepts and validate their behavior or to conduct trade-off studies for technological design. These multi-physics intensive simulations involve complex algorithms based on the use of a variety of mathematical libraries (random number generators, Fourier transform, and BLAS LAPACK routines). It exists, for these libraries, optimized versions generally distributed by hardware manufacturers that can be called individually with a standard, more or less portable, set of instruction. An innovative approach, appeared for less than ten years in the field of high performance computing, is to use hardware accelerators such as reprogrammable graphics processors (GPU) to overcome the limitations of the x86 architecture and maximize both the computing power / cost ratio and the computing power / required energy ratio. We proposed the implementation of a numerical development platform for AO, COMPASS, including: a full scale end-to-end simulation tool for AO with different dimensioning, a real time core that can be integrated directly on a real system and a prototype for low latency acquisition system. The development of this platform is based on a full integration of the software with the hardware and relies on the optimized migration of a simulation to a heterogeneous architecture using the GPU as accelerators. Research areas are diverse: AO modeling, real-time control in open or closed loop, acquiring images at low latency and science with AO in the context of the E-ELT instrumentation. It is a multidisciplinary collaboration combining the skills of specialists in astrophysics, instrumentation for large telescopes and high-performance computing. The project, which started in March 2013, brought together the effort of teams from six partner laboratories in France. The platform is fully functional today and can be used to simulate single conjugate AO with natural guide stars, as well as a multi-Laser tomographic AO on telescopes of different scales and with proven efficiency. Beyond the scientific exploitation of the platform that has already begun, the project is now directed towards the development of a distributed mode in order to run simulations on computer clusters equipped with GPU and thus target the largest scales AO systems while minimizing the simulation time. Significant work must be conducted on optimizing the code to make it adaptable to distributed architectures and minimize its memory footprint while maximizing performance. A user interface in Python has been developed to enable faster adoption by the community. The goal is to make this simulation platform a standard tool for the development of telescopes with extreme diameters. We will present the current status of the platform, the achieved performance on a variety of AO dimensioning and the long term maintenance plan.

9909-287, Session PThu1

Wavefront reconstruction with pupil fragmentation: study of a simple case

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The use of smaller subapertures on some recent adaptive optics systems and the presence of a thick spider in the telescope seem to yield difficulties in wavefront reconstruction. This is known as spider effect or pupil fragmentation. On these configurations, the width of the telescope spider is no more negligible compared to the size of the subapertures, and may hide full rows of subapertures. As results, the spider divides the pupil in disconnected domains, with missing or damaged measurements between them. An unseen mode made of differential pistons between the disconnected domains is then created. This effect has been clearly shown on E-ELT simulations and could be a source of the so-called SHERE low-wind effect. The difficulty is to derive the best wavefront reconstructor with such a pupil fragmentation.

In order to analyze this phenomenon, we have studied wavefront reconstruction on a simple small AO system with and without spider. The performances of various wavefront reconstructors are compared for different signal to noise ratios, using priors (minimum variance) or not (least-square) and with different assumptions for the missing wavefront measurements. The missing measurements have been either replaced by zeroes, or derived from an extension technique, or simply weighted to zero. Priors have been introduced using the FrIM (Fractal Iterative Method) algorithm. Our study allows a better understanding of the best approaches to mitigate pupil fragmentation and the limits of these mitigations.

9909-290, Session PThu1

End-to-end simulations of the E-ELT/ METIS coronagraphs

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The direct detection of low-mass planets in the habitable zone of nearby stars is one of the most important science cases for future ELT instruments. One of the first-light E-ELT instruments is the mid-infrared imager and spectrograph METIS, which features vortex phase masks and apodizing phase plates (APP) in its baseline design. The AGPM (Annular Groove Phase Mask) is a charge-2 vector vortex coronagraph, obtained with rotationally symmetric subwavelength gratings etched into diamond substrates. Since its first light in the VLT/NACO instrument in late 2012, its results have been remarkable, with a series of new instruments in its portfolio (LBT/LMIRCam, Keck/NIRC2, VLT/VISIR). Its impressive characteristics (small inner working angle, high throughput, clear off-axis 360° discovery space, achromaticity, simplicity) make it an attractive solution for future E-ELT instruments, and METIS in particular. However, these characteristics will be strongly challenged by the non-circular, centrally obstructed E-ELT pupil and by the residual aberrations that degrade the wavefront in presence of atmospheric turbulence. In this work, we present end-to-end performance simulations, using Fourier optical propagation, of various METIS coronagraphic modes, including focal-plane vortex phase masks and pupil-plane apodizing phase plates. In a first step, we study the effect of the E-ELT pupil architecture (central obstruction and spiders) on the coronagraphic performance. We then describe the sensitivity to tip-tilt errors (pointing jitter). Finally, the atmosphere and the AO contributions are taken into account in a realistic way to predict

the METIS on-sky coronagraphic performance. The relative performance of various concepts will be compared, and the most promising solutions will be identified.

9909-293, Session PThu1

A procedure for fast calibrating a voice-coil actuated adaptive mirror based on FE model

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The Finite Elements Analysis method provides an accurate modeling of a thin glass shell deformable mirror actuated via voice coil actuators and sensed via capacitive sensors. In particular, the actuator influence functions, needed to build-up the system control matrix, can be numerically computed within a 2% difference with respect to the optical measurements, after an initial tuning of the model. The most relevant advantages of the FE technique, compared to the optical calibration with an interferometer, are reduced costs, low risks and a shorter telescope down-time. Moreover, it enhances the SNR of the high order modes affected by the measurement noise.

In this paper we present a conceptual study for the synthetic calibration of an adaptive mirror driven by voice coil actuators. The goal is to generate the simulated influence functions and the control matrix, in order to close the AO loop. The reference case is the on-telescope recalibration of a DM after refurbishment and/or modules replacement. This concept of numerical calibration, in particular, is well suited for the E-ELT M4 system, a 2.5 m adaptive mirror, segmented into 6 identical petals, where the control electronics is assembled in elements called bricks: its high degree of modularity makes the proposed calibration very effective.

9909-298, Session PThu1

Simulations of E-ELT telescope effects on AO system performance

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In this poster, we will study the impact of various telescope effects (like effect of wind on main structure, phasing errors etc) on the performance of AO systems (telescope-oriented AO and instrumentation). For example, we will show what kind of AO system (number of sub-apertures, frame-rate) is necessary to compensate for these effects, to get a fully seeing limited performance from the telescope.

9909-301, Session PThu1

Pseudo-analytic simulation of woofer-tweeter MOAO system: application to MOSAIC

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The future MOS (multi-object spectrograph) of the European ELT, MOSAIC, is designed to study the morphology and dynamics of a large number of small (≈1'') high redshift galaxies in parallel. This study will require the adaptive optics (AO) system to reach a sufficient level of ensquared energy of the PSF across a wide field of view (around 10 arcmin) which could be achieved by using multi-object OA (MOAO) technique. The numerous independent optical science channels of MOSAIC will be corrected using a ground layer (GL) compensation performed by the built-in deformable mirror of the telescope (called M4), complemented by a secondary tweeter DM in each science channel.

In order to estimate the performance of such a system, we use a pseudo-analytical approach developed in a previous article, based on the computation of the covariance matrix of the tomographic error (including aliasing error), followed by a PSF reconstruction algorithm. The covariance matrix of the tomographic error is derived from the knowledge of the minimum mean square error (MMSE) reconstructor and covariance matrices of measurements.

One of the strength point of the approach is to be applicable to ELT-scale simulations due to a highly parallel algorithm.

However, this method was previously limited to the case of a single MOAO DM.

One of the challenging parts of the adaptation of the previous approach for a 2-DM case is to define correctly the tomographic error which is spread between the 2 DMs. They will have in particular a different number of actuators which induce different fitting errors, and different influence function that do not necessarily match together.

We develop in this article how we have computed the tomographic error, using two different methods. The first method is approximate and fast, but models both DMs by using the influence functions and fitting error of the highest-order DM only. The second method is more thorough: it simulates the tomographic error on both DMs distinctively but needs much lager matrices resulting on a less time-efficient computation. We discuss and compare those methods and show how we have adapted our PSF reconstruction algorithms to cope with the 2 DMs case.

We will also comment some results obtained with this approach on a MOSAIC case. In particular, we will discuss the performance versus the number of actuators of the secondary DMs.

9909-304, Session PThu1

Accurate laser guide star wavefront sensor simulation for the E-ELT first light adaptive optics module

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MAORY will be the multi-conjugate adaptive optics module for the E-ELT first light.

In order to ensure high quality correction across a Field of View of ~ 2 arcmin and high sky coverage, the baseline is to operate wavefront sensing using six Sodium Laser Guide Stars (LGS).

Three Natural Guide Stars (NGS) are also reguired to solve intrinsic

limitations of artificial beacons (tip-tilt indetermination and anisoplanatism) and to mitigate the impact of the sodium layer structure and variability.

The real impact of sodium layer behaviour on a 40 meter class adaptive telescope has never been measured, but recent studies based on simulations suggest that it might be not negligligible. In particular, some critical components of the AO system require to be designed and dimensioned in order to reduce the spurious effects arising from the Sodium Layer density distribution and variation.

It is then clear that becomes crucial to have a simulation code able to reproduce in a very accurate way the real sodium layer characteristics.

The MAORY end-to-end simulation code has been designed to accurately model the LGS image in the Shack-Hartmann wavefront sensor subapertures and to allow sodium profile temporal evolution.

The code allows also the simulation of transverse structures, possibly leading to differential effects among the Laser Guide Stars.

The fidelity with which the simulation code translates the sodium profiles in LGS images at the Wafront Sensor focal plane has been verified using a laboratory prototype.

9909-305, Session PThu1

Preparation of AO-related observations and post-processing recipes for E-ELT HARMONI

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HARMONI is a visible and near-infrared integral field spectrograph, providing the E-ELT's core spectroscopic capability. It will exploit the E-ELT's scientific niche in its early years, starting at first light. To fully exploit the spatial resolution and collecting power gain of the E-ELT, HARMONI will rely on the telescope's adaptive M4 and M5 mirrors. Two different adaptive optics (AO) systems will be used enabling both high-performance combined with low sky coverage using bright natural guide stars (SCAO) and medium performance combined with excellent sky coverage using 6 laser guide stars and faint natural guide stars for low-order correction (LTAO).

In this paper, we present numerical simulation results for the SCAO and LTAO modules of HARMONI in order to prepare observation strategies and post-processing recipes. First, an end-to-end model delivering highly accurate performance estimation is used, taking into account different aspects of the AO loop such as specific technology constrains (e.g. DM geometry, actuator stroke…), telescope configuration and limitations (e.g. spiders, LGS spot elongation…) and detailed aspects of AO control laws (e.g. calibration strategy, telescope transient regime…). We present a trade-off study and performance analysis for the choice of NGS WFSs, namely between Pyramid and Shack-Hartmann. LTAO performance is also addressed.

Complementary to the end-to-end modelling, a second model enables an efficient search of key AO parameters without relying on heavy computations. This enables us to quickly cover a large space of parameters and have a global view of performance. Realistic PSFs are rapidly generated and directly integrated in HSIM a full end-to-end HARMONI simulation tool. This will be used by the community to estimate the final performance of the instrument for specific science cases.

9909-307, Session PThu1

Deriving comprehensive error breakdown for wide field AO systems using end-to-end simulations

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Future European Extremely Large Telescope (E-ELT) adaptive optics (AO) systems, such as Multi Object Adaptive Systems (MOAO), will aim at wide field correction and large sky coverage thanks to the use of laser guide stars (LGS). However, AO correction is only partial and images obtained with such systems can be improved by using post processing techniques for image inversion relying on a field dependent point spread function (PSF). This requires an accurate knowledge of the PSF and its variations over the science field. The PSF estimation involves characterization of the different sources of error in the AO system from the wave front sensor data. Estimating and disentangling the various error contributors is an issue due to propagation and filtering process in the AO loop, and numerical simulations are a good way to address it. However, each simulation step at the E-ELT scale is very demanding in terms of computing power and data flow, and the simulation of a long exposure PSF requires several thousands of them. Moreover, the error breakdown estimation usually requires to perform several simulations to identify the different contributors. Hence, we use COMPASS (COMputing Platform for Adaptive opticS Systems), an end-to-end simulation tool especially developed to reach acceptable simulation time for ELT scales using GPU acceleration. We have developed in COMPASS an estimation tool that provides a comprehensive error breakdown on output of a single simulation. This is done by using known internal quantities computed by the simulation to estimate on the fly the impact of those errors on the E-ELT AO system performance without interrupting the main AO loop. This error budget returns, for example, the contribution of tomography (reconstruction) error, aliasing, fitting, noise on the wavefront sensor, or temporal error due to the loop delay. After a description of the error breakdown to be computed, we outline the estimation methods and its implementation in COMPASS and we discuss the results obtained on E-ELT scale cases.

9909-309, Session PThu1

8s: a simulator for the optical calibration of the E-ELT M4

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8s (Optical Test TOwer Simulator) is a simulation tool for the optical calibration of the E-ELT deformable mirror M4 on its test facility. It has been developed to identify possible criticalities in the procedure, evaluate the solutions and estimate the sensitivity to environmental noise.

The simulation system is composed by three parts: the finite elements model of the test facility, including its thermo-mechanical behaviour and the positioning devices; the analytic influence functions of the actuators, 886 for each of the 6 shells (petals); the propagation, via a ray-tracing program, of the laser beam from the interferometer through the optical surfaces, each placed at the position defined by the user.

The tool delivers simulated phasemaps of M4, associated with the current

system status: actuator commands, optics alignment and position, beam vignetting, bench temperature and vibrations. It is possible to simulate a single step of the optical test of M4 by changing the system parameters according to a calibration procedure and collect the associated phasemap for performance evaluation.

In this paper we will describe the simulation package and outline the proposed calibration procedure of M4.

9909-310, Session PThu1

The numerical simulation tool for the MAORY multiconjugate adaptive optics system

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We developed a numerical simulation tool for the end to end simulations of the Multiconjugate Adaptive Optics RelaY (MAORY) for the ESO European-Extremely Large Telescope.

MAORY will implement Multiconjugate Adaptive Optics (MCAO) correction through three high order deformable mirrors driven by the reference signals of six Laser Guide Stars (LGSs) feeding as many Shack-Hartmann wavefront sensors. A three Natural Guide Stars (NGSs) system will provide the low order correction. The simulation tool is based on the IDL language performs a Monte-Carlo modeling of the MAORY system performance through an extensively usage of the available GPUs. Here we recall the code architecture and describe the modeled instrument components and the control strategies we implemented. The NGS system limiting magnitude and its interaction with the LGS adaptive loop is fundamental to consolidate the design of the MAORY. Here we present as an example exercise the application of the code to obtain sky coverage information.

9909-311, Session PThu1

Simulation of solar adaptive optics systems

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Solar adaptive optics (AO) simulations are a valuable tool to guide the design and optimization process of current and future solar AO and multi-conjugate AO (MCAO) systems. Solar AO and MCAO systems rely on extended object cross-correlating Shack-Hartmann wavefront sensors (SHWFS) to measure the wavefront. Accurate solar AO simulations require computationally intensive operations, which have until now presented a prohibitive computational cost.

We present an update on the status of a solar AO and MCAO simulation tool being developed at the National Solar Observatory. The tool provides accurate full simulation of solar AO and MCAO systems. In particular, it accurately simulates the imaging processes that produce the non-zero field-of-view sub-aperture images of the cross-correlating SHWFS. Such simulations are very computationally intensive and strongly benefit from fast and heavily parallelized code. Our simulation tool is a multi-threaded application written in the C++ language that takes advantage of current large multi-core CPU computer systems and fast ethernet connections. It interfaces with KAOS, a state of the art solar AO control software developed by the Kiepenheuer-Institut fuer Sonnenphysik (KIS), that provides reliable AO control.

We will report on the latest results produced by the solar AO simulation tool. In particular, applied to an optimization study of the reconstruction strategies used by the high order solar AO system, currently under development for the 4 m class DKIST solar telescope; and to a performance optimization study of the prototype solar MCAO system at the Big Bear Solar Observatory.

9909-313, Session PThu1

Effects of the outer scale on the adaptive optics simulations

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In the context of the characterization of the performances of adaptive optics instruments the intensive use of numerical simulation tools is a common praxis. The outer scale (L0) is in general assumed constant in space and time in the sense that all phase screens assume the same value of L0 that does not change with time. Typical numerical end to end simulations last a few hours but represent a shorter time of the instrument system evolution. This means that if we assume on the contrary that L0 changes in space and time different values of L0 might have in this temporal range a different impact on the simulations outputs. These potential effects are in reality disregarded and not taken into account at present time. Moreover a disregard of the outer scale effects brings to take less care of the modeling of this parameter. Besides, in most of the cases, vertical distribution of the outer scale is not taken into account in the common practice of the adaptive optics simulations because all phase-screens assume in general a similar outer scale. In single conjugate adaptive optics (SCAO) the more important effects of a different vertical distribution of the L0 should be expected on the performance off-axis. However the outer scale vertical distribution becomes more and more important when the field of view becomes larger and larger. In wide field of view adaptive optics (WFAO) the proper modeling of the effect of the distribution may induce the system analysis and adaptive optics engineers to tune differently the adaptive optics control system parameter in order to best match the environment conditions. A set of test cases will be considered in order to identify critical conditions and figures of merit for the simulations of different AO systems.

9909-314, Session PThu1

PASSATA: object oriented numerical simulation software for adaptive optics

Guido Agapito, Alfio T. Puglisi, Simone Esposito, INAF - Osservatorio Astrofisico di Arcetri (Italy)

We present the last version of the PyrAmid Simulator Software for Adaptive opTics Arcetri (PASSATA), an IDL and CUDA based object oriented software developed in the Adaptive Optics group of the Arcetri observatory for Monte-Carlo end-to-end adaptive optics simulations. The original aim of this software was to evaluate the performance of a single

conjugate adaptive optics system for ground based telescope with a pyramid wavefront sensor. After some years of development, the current version of PASSATA is able to simulate several adaptive optics systems: single conjugate, multi conjugate and ground layer, with Shack Hartmann and pyramid wavefront sensors. It can simulate from 8m to 40m class telescopes, with diffraction limited and resolved sources at finite or infinite distance from the pupil. The main advantages of this software are the versatility given by the object oriented approach and the speed given by the CUDA implementation of the most computational demanding routines. We describe the software with its last developments and present some examples of application.

9909-315, Session PThu1

Soapy: an adaptive optics simulation written purely in Python for rapid concept development

Andrew P. Reeves, Durham Univ. (United Kingdom)

Simulation is essential to specify, design and characterise existing and future Adaptive Optics (AO) systems. To this end, many codes exist which aim to run as quickly as possible over large parameter spaces, requiring extreme optimisation and parallelisation to do so. Whilst making these simulations fast, these techniques can also make it difficult to implement new features, such as Wave Front Sensor (WFS) concepts or new reconstructors. It can also make them difficult for those new to the field of AO to understand.

To address these requirements, we present the "Simulation Optique Adaptative in Python" (Soapy) package. Soapy is written purely in "Python", a high level, interpreted language to facilitate rapid development of new AO concepts. The code is modularised so different components, such as WFSs or deformable mirrors, can be used stand-alone. Modules can be easily extended, as core interfaces and functionalities are provided by "base" classes, allowing a developer to add new and interesting capabilities without writing much extra code. There is also a strong focus on clear documentation throughout the package to allow the user to be able to quickly understand the simulation and its internals.

Accurate simulation of Laser Guide Stars (LGS) is a focus for Soapy. Sodium LGS elongation is simulated by propagating the LGS beam down from a discrete number of altitudes within the sodium layer, which provides realistic simulation of differential focus and angular anisoplanatism between light from the top and bottom of the sodium LGS plume. LGS uplink effects are also simulated, which can use either a geometric ray tracing, or physical optical approach. Physical light propagation for downlink WFS light from either NGS or LGS is also supported, allowing studies into the effects of scintillation.

Soapy is currently in use within the Centre for Advanced Instrumentation (CfAI) at Durham University, for investigating novel laser guide star schemes. It is open source, and has proven popular amongst PhD. students and staff within the CfAI as a learning tool and for early AO concept development.

9909-316, Session PThu1

Adaptive optics (AO) system modeling performance investigation of the 4m DAG telescope

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This paper consists of the investigation of the expected performance of DAG telescope's GLAO system. While the GLAO approach uses a few bright stars to measure the wavefront perturbations in different directions and to implement corrections over a large field of view, it's a versatile system. If angle of guide stars are decreased to zero, the system becomes a classical adaptive optics system. In order to validate the optical performance of the system a MATLAB model comprised of the models of the optical elements of the system is built. The optical elements used in this model consist of a deformable mirror, a tip/tilt mirror, a control algorithm and a Shack-Hartmann wavefront sensor. Based on the site telemetric data, the result of the expected performance of DAG telescope with and without AO compensation will be presented.

9909-317, Session PThu1

Simulation study on Shack-Hartmann wavefront sensor spots centroid detection optimized algorithm

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The threshold selection method for the spot image of Shack-Hartmann Wavefront Sensor (SH WFS)has a large influence on the centroid detection accuracy. This paper built an adaptive optics system simulation model based on wave optics theory. The influence of stray light and noise in complicated optics system on the features of spot image of a SH WFS was simulated, and the effect of the threshold of spot image on the centroid detection accuracy and wavefront reconstruction was studied, and then an adaptive optimized threshold selection method was presented. The threshold was intended to be the percentage of maximum spot energy by analyzing the effect of stray light and noise on the farfield image. The thresholds of each lenslet spot were adaptive selected by the same percentage. The results show that the method can effectively and automatically select the threshold of each frame image. The SH WFS with the threshold selection method is used in the adaptive optics system to carry out a closed-loop correction experiment. After correction, the RMS of wavefront rest distortion was improve by 60% above than simple threshold select method. Compared with ordinary methods, this method was proved more effective in extend object situation. These results showed the method can meet the practical requirements of SH WFSs.

9909-318, Session PThu1

Analysis of the performances of 45 degrees tilted deformable mirrors for the EST MCAO

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The European Solar Telescope (EST) will be best suited for very high accuracy polarization measurements. Indeed, its optical design is such that the telescope as a whole does not modify the polarization state of the incoming light. For this reason, a mutually compensating configuration with 45° degrees tilted deformable mirrors (DMs) is proposed for its multi-conjugated adaptive optics (MCAO) system. In this work we present preliminary results about the analysis of this non-standard configuration, and the impact of DMs with large incidence angles on the overall performances of the MCAO system.

9909-319, Session PThu1

The software package CAOS 6.0: enhanced numerical modeling of astronomical adaptive optics systems

Marcel Carbillet, Lab. J.L. Lagrange (France)

The Software Package CAOS (acronym for Code for Adaptive Optics Systems) is a modular scientific package performing numerical modeling of astronomical adaptive optics (AO) systems. It is IDL-based and developed within the homonymous CAOS "problem-solving environment". In this paper we present the last version of the Software Package CAOS, which contains a number of enhancements and new modules, e.g. for ground-layer and multi-conjugate AO. Examples of application will also be given, in particular for what concerns the newly projected AO system CIAO@C2PU.

9909-271, Session PThu2

PSF calibration using the low-order wave front sensor telemetry

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High performance small inner working angle (IWA) coronagraphs equipped with ground-based extreme adaptive optics systems are capable of imaging exoplanets in their habitable zone. However, their performance is constrained by how well the wavefront aberrations can be controlled and calibrated. The uncorrected residual wavefront aberrations scatter the starlight, which produces intensity fluctuations and as a result creates dynamic speckle noise in the focal plane. Techniques like angular differential imaging can calibrate out the static and quasi-static features of the PSF but becomes less effective at angular separation smaller than 0.5". In order to improve the post processing of the science images at small IWA, the low-order telemetry of the residuals left uncorrected by the control loop can be used to calibrate the amount of starlight leakage at small angular separations.

To address low-order aberrations in small IWA phase mask coronagraphs, a Lyot-based low-order wavefront sensor (LLOWFS) has been developed. This sensor reliably measures up to 35 low-order Zernike modes using the starlight reflected by the Lyot stop and is operational on the SCExAO instrument at the Subaru Telescope. Using LLOWFS images, the PSF can be calibrated by recording synchronized low-order measurements and science camera frames that are used to build a library of response of the residuals on the starlight leakage. During the observation of the science target, LLOWFS residuals can be fitted with the best match in the library. The corresponding science equivalents can then be subtracted from the science image to reconstruct the PSF. This technique can significantly improve the sensitivity of a coronagraph. In this body of work, we will present the preliminary results of PSF reconstruction using the LLOWFS measurements for a H-band vector vortex coronagraph.

9909-274, Session PThu2

Point spread function reconstruction for multi-conjugate adaptive optics

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In the upcoming generation of Extremely Large Telescopes (ELT), with mirror diameters of up to 40 m, the impact of the turbulent atmosphere is corrected by wide field Adaptive Optics (AO) system, such as Multi-Conjugate Adaptive Optics (MCAO) within the Multi-AO Imaging Camera for Deep Observations (MICADO) of the European ELT.

Even with AO correction, the quality of astronomical images still is degraded due to the time delay stemming from the wavefront sensor (WFS) integration time and adjustment of the deformable mirror(s) (DM). This results in a blur which can be described by the point spread function (PSF). The PSF of an astronomical image varies with the position in the observed field, which is a crucial aspect in MCAO on ELTs. With the knowledge of the PSF, the quality of the AO correction can be measured and furthermore the image quality can be improved using deconvolution algorithms.

We analyze and present a combined approach for PSF reconstruction throughout atmospheric tomography which is based on the algorithm by J.-P. Veran developed for Single Conjugate AO systems. Our PSF reconstruction algorithm combines existing, verified techniques in a novel way to deliver accurate field dependent PSFs in very short time. With the use of atmospheric layers reconstructed from WFS data, it is possible to determine pseudo wavefronts in different observation directions, which can be used not only to derive the DM shape(s) for the best possible correction, but also in Veran's algorithm to overcome the problem of field dependence of the PSF.

Our simulation results are obtained for the ELT setting in OCTOPUS, the ESO end-to-end simulation tool. For a variety of atmosphere and system parameters, they suggest a good qualitative performance along with reasonable computational effort.

9909-278, Session PThu2

Compensated diffraction-limited imaging with adaptive optics at the GREGOR Solar Telescope

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The combination of adaptive optics with post processing of sequences of short exposures is a very successful technique to produce diffraction limited images of the solar photosphere throughout the visible spectral domain. Viable approaches are multi frame blind deconvolution and speckle imaging, and both approaches have been used with great success in the past 15 years. While blind deconvolution solves for both the undisturbed image and the optical transfer function for every frame in the sequence, speckle imaging makes assumptions about the statistics of the partially compensated wavefront and the resulting transfer functions which apply to the speckle signal. These depend on the shape of the entrance aperture and on the characteristics and performance of the adaptive optics system, and therefore need to be established separately for every telescope.

We have calculated the speckle transfer function (STF) for the GREGOR solar telescope as a function of seeing and control performance of GREGORs adaptive optics system GAOS. The calculations are based on simulations of optical propagation through an extended, turbulent atmosphere and field dependent, partial compensation by a conventional adaptive optics system. The compensation characteristics are based on actual measurements of the performance of GAOS. We present the results of the simulations and compare image reconstruction using the simulated transfer functions with reconstructions based on the previously used analytic STF models.

9909-281, Session PThu2

Spatially variant PSF modeling and image deblurring

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Regularized image deconvolution is a powerful tool to achieve the ultimate spatial and spectral resolution from astronomical data. However, in their quest for observing larger and larger fields of view and collecting spectral and spatial information at the same time, the astronomical instruments are becoming more and more complex and their point spread function (PSF) is no longer stationary. In words, a simple convolution cannot properly approximate the instrumental blur and, as a consequence, a deconvolution cannot remove this blur. Thus, in an increasing number of cases, the deblurring of astronomical images poses a triple problem. First, a good approximation of a shift-variant blur is needed. Second, image restoration methods must be adapted to use such a model. Third, practical means to calibrate a shift variant blur must be found. In this contribution, we quickly review existing blur models with a particular emphasis on the models which are the most suitable for astronomy and for being used in restoration methods. For instance, with a non-stationary blur the deblurring methods must be iterative and having a fast model is important. We will show that improved results can be obtained in a variety of astronomical contexts when the proper shift variant blur model and image restoration method are used. In particular, correctly taking into account a shift-variant blur is of major importance to correctly estimate physical parameters such as the photometry, the shape and the position of the observed objects. Finally, we will present preliminary results concerning the estimation of the shift-variant blur in practice.

9909-283, Session PThu2

PSF Reconstruction for the Keck integral-field spectrograph OSIRIS

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We discuss a method for predicting laser guide-star adaptive optics (LGS AO) point spread functions (PSFs) on an integral-field spectrograph (IFU) based on off-axis parallel imaging and measurements of atmospheric turbulence. Because the field of view of IFUs are very small, it is often not possible to sample the PSF over a large radial range. For extended sources, it is even more difficult to obtain reliable estimates of the PSF. The OSIRIS instrument on the Keck I telescope consists of both an imager and an IFU that can be used simultaneously for PSF measurements. However, the center of the imager is separated by about 20" from the center of the IFU, so it is necessary to correct for anisoplanatism and differences in instrumental aberrations between the imager and IFU. This method begins with measurements of point sources with the imager to obtain an off-axis empirical PSF. Then, we use the knowledge of the atmospheric turbulence profile obtained with MASS/DIMM measurements, and measurements of the instrumental aberrations to deconvolve the empirical PSF to obtain an estimate on the spectrograph. We also model the wavelength dependence of the PSF as well as the effect of different integration times between the observations on the imager and the spectrograph. This technique is based on tools developed for AO PSF reconstruction with the NIRC2 imager on Keck. We will present preliminary results on observations of the Galactic center, where the crowding from stars make PSF determination especially difficult on the IFU. We will discuss metrics for the comparison such as the level residuals and the effect on the final signal-to-noise ratio of the extracted spectra. We will release these tools to the community at the end of the project.

9909-286, Session PThu2

Speckle statistics in adaptive optics images at visible wavelengths

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Residual speckles in adaptive optics (AO) images represent a well known limitation to the achieve of the minimum contrast needed for faint stellar companions detection. Speckles in AO imagery can be either the result of residual atmospheric aberrations not corrected by the AO, or slowly evolving aberrations induced by the optical system. In this work we take advantage of new data with very high frame rate (1 KHz) acquired from the SHARK forerunner experiment at the Large Binocular Telescope (LBT), to provide a characterization of the AO residual speckles. By means of an automatic identification of speckles, we outline the main statistical properties of AO residuals at visible wavelength, and study the memory of the process, and the clearance time of the atmospheric aberrations, by using the information theory. These information are important either for increasing the realism of numerical simulations aimed at assessing the instrumental performances, or for the application of post-processing techniques on AO imagery.

9909-289, Session PThu2

A comparison between different coronagraphic data reduction techniques

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A solid post processing technique is mandatory for analysing the coronagraphic high contrast imaging data. Angular Differential Imaging (ADI) and Principal Component Analysis (PCA) are the most used approaches to suppress the quasi-static structure presents in the Point Spread Function (PSF) for revealing planets at different separation from the host star.

We present the comparison between ADI and PCA applied to SHARK-NIR, a coronagraphic camera which will be implemented at LBT. The

comparison has been carried out by using as starting point the simulated wavefront residuals of the Large Binocular Telescope Adaptive Optics (LBT AO) system, in different observing conditions.

Accurate tests for tuning the post processing parameters to obtain the best performance from each technique were performed with various seeing conditions (0.4" – 1.2") for star magnitude ranging from 8 to 12, with particular care in finding the best compromise between quasi static speckle cancellation and planets detection. The quasi static speckle contribution introduced in the simulations has been tuned based on real data observations performed on sky.

For the simple ADI version a reference PSF is obtained by taking the median of all images in the sequence (we also analysed the possibility to perform a second reference PSF subtraction using the median of few images as close in time as possible) and then subtracted to each image to remove the quasi-static structure. To mimic the real procedure, after the inclusion of fake planets in the simulated data-cubes, all the image differences are de-rotated to align the FoV and finally a final median is performed. A minimum FoV rotation of 30-50 degrees is considered, in order to make sure that even at small angular separations the signal from the possible companion after the subtraction would be largely preserved.

We evaluated also the implementation of the PCA techniques, that is based on a mathematical representation of each frame in the data-cube as a linear combination of its principal orthogonal components by selecting the structures present in most of the images. Its application has been reported to be very effective particularly by manipulation of the number of PCs to maximize the signal from the planet near its host star.

The detection limits are calculated using the ratio of simulated planets peak intensities over the noise in the residual image as a function of the angular separation, to take into account the cancellation value due to the used post processing technique.

9909-291, Session PThu2

Metrics and quality control with adaptive optics instruments at the VLT

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There are many Adaptive Optics (AO) fed instruments on Paranal and more to come. To monitor their performances and assess the quality of the scientific data, we have developed a scheme and a set of tools and metrics adapted to each flavour of AO and each data product. Our decisions to repeat observations or not depends heavily on this immediate quality control "zero" (QC0). Atmospheric parameters monitoring can also help predict performances . At the end of the data production chain chain, the user must be able to get data matching his/her needs translated into a set of requirements based on simulations done with an exposure time calculator (ETC). Predictions and real performances must match and the assessment must be intelligible to the community. We will emphasis on the difficulties encountered to perform quality control with SPHERE and the need for different metrics at various levels of wavefront: i.e Strehl ratio and FWHM for SCAO/LTAO/MCAO, contrast for an xAO, EE for GLAO, etc.

9909-296, Session PThu2

PSF reconstruction for the MUSE-GALACSI GLAO mode in Python

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The use of AO systems is growing at an increasing rate and ESO is already preparing the next generation of AO instruments for both the VLT and the E-ELT.

Even though the corrected images obtained with these instruments are closer to the ultimate diffraction limit, the correction is not perfect, particularly in the case of a large Field of View. Thus, it is often necessary to use a posteriori image processing techniques in order to improve estimation of astrophysical data.

These techniques require accurate knowledge of the system's PSF in an arbitrary position in the Field of View. We present a PSF reconstruction software which estimates the PSF in the particular case of the MUSE/GALACSI instrument. It includes the Field of View location and wavelength dependencies.

9909-297, Session PThu2

The software package AIRY 7.0: new efficient deconvolution methods for post-adaptive optics data

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The Astronomical Image Restoration in interferometrY (AIRY) software package is a complete tool for the simulation and the deconvolution of astronomical images. The typical data can be a set of Fizeau interferometric multiple images as well as a more general case of post-adaptive-optics single image or even a mono-dimensional signal. Written in IDL and freely downloadable from both http://www.airyproject.eu and http://lagrange.oca.eu/caos websites, AIRY is a package of the CAOS Problem Solving Environment. It is made of different modules, each one performing a specific task, e.g. simulation, deconvolution, I/O, and visualization of the data.

In this paper we first present the last major release of AIRY with a short description of the whole set of modules. Then, we introduce a new optimized method for the deconvolution problem, based on the scaled-gradient projection (SGP) algorithm which has been recently extended with a set of regularization functions. The existing algorithms within the deconvolution module (DEC) are flanked by the new method proposed here. Moreover, we provide a brief description of the renewed DEC's graphical user interface.

Next, we introduce a new multi-component deconvolution (MCD) module, which contains a method developed in the last years by our group for deconvolving high dynamic range images. Indeed, in particular cases, the unknown object is made of one or more bright point-like sources superimposed on a fainter diffuse component. Our multi-component algorithm is able to separately reconstruct the two components. MCD uses the SGP-based new algorithms just introduced in DEC.

In the last part of the paper we describe our multi-step method, developed in 2015 by our group. This method is very useful, again, in the case of

high dynamic range images and it is an extension of the multi-component method. We give some example projects (provided together with the Software Package AIRY) in order to show each step and the main results achievable with this approach.

By using AIRY v.7.0, users have a powerful tool for simulating the observations and for reconstructing their real data.

9909-302, Session PThu2

Post-processing of multispectral images for exoplanets detection and characterization: the MEDUSAE algorithm

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The new generation of high contrast instruments for ground-based telescopes that are dedicated to exoplanet imaging are all equipped with an Integral Field Unit (IFU), such as SPHERE/IFS, GPI and SCExAO/CHARIS in order to obtain spectra of the observed objects. Despite the advanced technologies constituting these instruments, they are still limited by the presence of quasi-statics speckles in the image field that are due to remaining instrumental aberrations. Advanced image processing tools can be used to separate these speckles from the scientific signals, taking advantage of the different spectral behavior of these two components.

MEDUSAE (Multispectral Exoplanet Detection Using Simultaneous Aberration Estimation) is an image processing method that specifically uses the spectral diversity of multispectral images to detect and characterize exoplanets. This method is based on an inverse problem solving algorithm, which jointly estimates the instrumental aberrations and the astrophysical scene. The multispectral redundancy is used to estimate the optical path differences and the positions of the companions, which are the same whatever the wavelength. The estimation is alternate between the speckle field (estimated thanks to a phase retrieval) and the object map (estimated via a non-myopic deconvolution).

This algorithm has been successfully validated on simulated data built with the same model than the one used to solve the inverse problem. We present results from the application of this algorithm on real data from the VLT/SPHERE-IFS instrument. In particular, we comment the discrepancy between the model and the real data, mostly about the coronagraph behavior compared to its model which is ideal (all the on-axis starlight is rejected). We also discuss which prior knowledge can be included in the algorithm, either from instrument calibrations or analytical estimations, to assess the static wavefront error and the turbulent wavefront residuals. We then present its overall performance on real data by analyzing on-sky images in which we injected fake companions to assess the detection and spectral extraction capabilities of MEDUSAE. Finally we present how it compares to other algorithms exploiting the temporal variation of the images that are widely used by the exoplanet direct imaging community because they are the most efficient in subtracting the starlight residuals. Also, the chosen approach brings useful insights regarding the co-design of the future ELT's instruments, together with their calibration procedures and the methods chosen to process the produced images.

9909-303, Session PThu2

ABISM: an interactive image quality and Strehl ratio measurement tool for adaptive optics instruments

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ABISM (Automatic Background Interactive Strehl Meter) is an interactive tool to evaluate the image quality of astronomical images. It works on seeing-limited point spread functions (PSF) but was developed in particular for diffraction-limited PSF produced by adaptive optics (AO) systems. In the VLT service mode (SM) operations framework, ABISM is designed to help astronomers or telescope operators to quickly measure the Strehl ratio (SR) during or right after an observing block (OB) to evaluate whether it meets the requirements/predictions or whether is has to be repeated and will remain in the SM queue. It's a Python-based tool with a graphical user interface (GUI) that can be used with little AO knowledge. The night astronomer (NA) or Telescope and Instrument Operator (TIO) can launch ABISM in one click and the program is able to read keywords from the FITS header to avoid mistakes. A significant effort was also put to make ABISM as robust (and forgiven) with a high rate of repeatability. As a matter of fact, ABISM is able to automatically correct for bad pixels, eliminate stellar neighbours and estimate/fit properly the background, etc. We present an update and a partial release of this handy quality control tool.

9909-306, Session PThu2

Detection of faint companions in multi-spectral data using a maximum likelihood approach

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Direct, ground-based exoplanet detection is an extremely challenging task requiring extreme adaptive optics (AO) systems and very high contrast. Dedicated planet hunters, such as SPHERE and GPI have been designed with these requirements in mind. Despite this, direct detection is still limited due to the presence of residual speckles.

Smith et al. (2009) describe a maximum likelihood estimation technique for the detection of exoplanets in speckle data in which the planet appears to rotate about a host star when observing with an alt-az telescope.

We propose the adaptation of this technique to operate on multi-spectral data, such as produced by the integral field spectrographs present on both SPHERE or GPI.

As the speckle pattern approximately scales smoothly with wavelength, it is possible to resample data to a single reference wavelength in which speckles will remain fixed in the wavelength dimension while any companions that are present will exhibit radial motion in a predictable manner. We simulate data comparable to SPHERE and with this, we compare the performance of our algorithm with other multi-spectral detection techniques, such as spectral deconvolution.

We compare the techniques using a ROC (Receiver Operating Characteristic) analysis.

Results have shown that the performance of our maximum likelihood algorithm is found to be superior at separations smaller than 0.5 arcseconds from the host star and comparable beyond that.

9909-308, Session PThu2

Point spread function reconstruction on the HeNOS bench

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This paper reports on point spread function reconstruction (PSFR) work on the Herzberg NFIRAOS Adaptive Optics Simulator (HeNOS) bench at NRC-HIA. An initial set of experiments was carried out in March 2016 with the bench running in laser guide star (LGS) single-conjugate adaptive optics (SCAO) mode or laser tomography adaptive optics (LTAO) mode. We discuss data acquisition and data reduction. An analysis of angular and focal anisoplanatism is also carried out.

LGS multi-conjugate adaptive optics (MCAO) experiments are planned for the second half of 2016 and will be reported elsewhere.

9909-272, Session PThu3

E-ELT M4 adaptive unit final design and construction: a progress report

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The E-ELT M4 adaptive unit is a fundamental part of the E-ELT: it provides the facility level adaptive optics correction that compensates the wavefront distortion induced by atmospheric turbulence and partially corrects the structural deformations caused by wind. The unit is based on the contactless, voice-coil technology already successfully deployed on several large adaptive mirrors, like the LBT, Magellan and VLT adaptive secondary mirrors. It features a 2.4m diameter flat mirror, controlled by 5316 actuators and divided in six segments. The reference structure is monolithic and the cophasing between the segments is guaranteed by the contactless embedded metrology. The mirror correction commands are usually transferred as modal amplitudes, that are checked by the M4 controller through a smart real-time algorithm that is capable to handle saturation effects. A large hexapod provides the fine positioning of the unit, while a rotational mechanism allows switching between the two Nasmyth foci.

The unit has entered the final design and construction phase in July 2015, after an advanced preliminary design. The final design review is planned for fall 2017; thereafter, the unit will enter the construction and test phase. Acceptance in Europe after full optical calibration is planned for 2022, while the delivery to Cerro Armazones will occur in 2023.

Even if the fundamental concept has remained unchanged with respect to the other contactless large deformable mirrors, the specific requirements of the E-ELT unit posed new design challenges that required very peculiar solutions. Therefore, a significant part of the design phase has been focused on the validation of the new aspects, based on both analysis, numerical simulations and experimental tests. Several experimental tests have been executed on the Demonstration Prototype, which is the 222 actuators prototype developed in the frame of the advanced preliminary design.

We present the main project phases, the current design status, and the most relevant results achieved by the validation tests.

9909-275, Session PThu3

Developments of piezo deformable mirrors

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We present recent developments on deformable mirrors (DMs) for astronomy with ground-based telescopes. Pioneer in the field of adaptive optics, CILAS has developed and manufactured for many years piezoelectric deformable mirrors. CILAS current technology is based on two types of deformable mirrors: Stack Array Mirrors (SAM) and Monomorph mirrors (MONO).

SAM technology offers high order correction, with up to several thousands of actuators, controllable at high frequency, up to several kHz. We present developments performed in collaboration with European Southern Observatory (ESO) and Thirty Meter Telescope (TMT). A new generation of piezo actuators has been developed. Their reliability has been improved thanks to an optimization of the fabrication processes while keeping the required correction performances. Experimental results of accelerated ageing tests and mechanical fatigue are presented. This new generation of actuators is suitable for a large range of DMs, including future needs for Extremely Large Telescopes (ELTs).

Modelling analysis and operational feedback of previous DMs allowed the improvement of the design and the fabrication of CILAS piezo-stack DMs. We present the design and the modelling of next DMs for adaptive optics systems on next ELTs: multi-conjugate DMs for NFIRAOS instrument on the TMT and DMs for Multi-conjugate Adaptive Optics RelaY (MAORY) on the European Extremely Large Telescope (E-ELT).

Performances of SAM have a low dependence to environment and temperature. A DM prototype with high stroke has been designed and is under manufacturing to validate the behaviour of SAM at low temperature (-30C) for TMT.

CILAS monomorph technology benefits from the great history of bimorph mirrors which have been commonly used to correct atmospheric turbulences on astronomical telescopes since 1996. Compared to the bimorph technology, the monomorph presents an optimized architecture which secures its manufacturing and increases its reliability. The monomorph mirrors benefits from a return of experience of 10 years with an unfailing reliability on ground from astronomical telescopes (adaptive optics) to high power laser chains (active optics).

Important developments are on-going for space-borne instrumentation. The associated analyses and tests confirm the reliability and the sturdiness of the MONO technology. Compared to the former bimorph mirrors, MONO technology presents higher intrinsic performances (optical quality, stroke) which can be exploited in closed loop but also in open loop. In-situ return of experience on high power laser chains demonstrates the extreme stability of the monomorph operating in open loop during the laser shots. In addition, a novel approach was developed to cancel the natural drift of the piezoelectric ceramics in open loop operation (so called “creep” effect). For ground-based telescopes requiring real-time correction of atmospheric turbulences, a specific mechanical interface was developed to cancel the first Eigen frequencies of the mirror and thus to increase its bandwidth. This technological breakthrough allows astronomical telescopes to take advantage of the developments of monomorph mirrors for laser applications including their large pupils of 250 mm diameter and more.

9909-276, Session PThu3

GMTIFS: deformable mirror environmental testing for the on-instrument wavefront sensor

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To achieve the high adaptive optics sky coverage necessary to allow the GMT Integral-Field Spectrograph (GMTIFS) to access key scientific targets, the on-instrument adaptive-optics wavefront-sensing system utilises a deformable mirror (DM) to provide an off-axis correction to the natural guide star. To avoid flexure concerns, this DM is located inside the instrument cryostat. Commercial off the shelf DMs are not able to operate in the cryogenic and vacuum environment of GMTIFS, therefore the DM must be housed in a windowed chamber within the instrument which is pressurised and warmed relative to the cryogenic environment. To reduce thermal emissions and additional heat load on the thermal control systems the temperature difference of the DM chamber and instrument is minimised. Thus a test is required to determine the lowest operating temperature at which the DM will meet the instrument performance requirements without significantly reducing reliability.

We will report on the optical system built to measure the performance of three DMs. Two continuous surface DMs are tested with the ALPAO DM69 and Boston Micromachines 492-DM. The third DM tested is an Iris AO PTT111 which is made of 37 individual piston, tip and tilt segments. These DMs provide an accurate representation for construction and performance of larger DMs which are considered for use in the GMTIFS OIWFS. The DMs are subject to a suite of static and dynamic tests where the surface of the DM is measured by a Shack Hartmann wavefront sensor (WFS). The WFS oversamples the DMs by approximately 4 subapertures per actuator to allow for measurement of the interactuator stroke. The WFS features a large dynamic range so resolution of between 1% of actuator stroke to full interactuator stroke is achieved, which gives a sensitivity of between <20nm and 5μm mirror surface deformations. High temporal sampling is also achieved for single actuator response measurements with sampling rates of at least 8kHz possible through region of interest selection.

Initial DM testing is conducted at room temperature to obtain a baseline for DM performance. The tests performed on the DMs measure the steady state mirror surface and actuator response while moving to a defined position. Cold testing will subject the DMs to identical tests with incrementally reducing temperatures. Tests are conducted down to a temperature of -60 degrees Celsius, however testing may cease at warmer temperatures if there is a risk of damage to the DMs. Comparison with the room temperature baseline tests provide an indication of the effects of cold temperatures to DM performance and any thermal effects to the structure such as surface ripple. The tests will determine the minimum temperature the DMs will operate within the instrument without significant performance degradation or increased risk of failure.

9909-284, Session PThu3

Long-term stability and temperature variability of Iris AO segmented MEMS deformable mirrors

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Iris AO has been developing microelectromechanical systems (MEMS) based deformable mirrors (DM) for a number of years. We currently manufacture two type of deformable mirrors, the PTT111 made of 37 hexagonal segments (111 actuators) and the PTT489 made of 163 hexagonal segments (489 actuators). Our mirrors are factory calibrated and can be positioned in piston and tip-tilt. This paper presents a study of the stability of several PTT111s deformable mirrors over about 2 years, focusing essentially on the stability of the open-loop positioning and the variability with temperature changes.

9909-288, Session PThu3

Development of a silicon carbide deformable mirror with 37 actuators for adaptive optics

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Adaptive optics (AO) were developed for military and astronomy applications, e.g., in telescopes to correct wavefronts distorted by the earth atmosphere and to obtain an undistorted image of stars and galaxies. Nowadays, AO systems have become more available and are used in various other fields including ophthalmology, microscopy, and underwater imaging. DMs used in high-power lasers (HPL), however, suffer from thermal distortion problems, where the energy absorbed by the DM due to the imperfect reflective coating distorts the faceplate and degrades the system performance. Therefore, DM for HPL systems must have an active or passive cooling system to dissipate the heat, and the proper selection of the faceplate material is also crucial.

In this paper, we deal with a silicon carbide (SiC) deformable mirror (DM) with 37 actuators for adaptive optics (AO). Compared with conventional optical glass materials, SiC has superior optomechanical properties, including extremely high specific stiffness and thermal conductivity and little distortion by thermal energy or pressure. Based on the study by Ealey et al (1992), we selected SiC as the faceplate material for the DM in HPL applications, as SiC has a high thermal diffusivity that effectively minimizes the mirror distortions due to thermal gradients. As a predecessor of the monolithic DM having active cooling channels inside, we developed a pilot DM made of silicon carbide (SiC) for HPL applications to verify the fabrication capability and actuation performances. The DM has a continuous SiC faceplate, the diameter and the thickness of which are 100 mm and 2 mm, respectively, and 37 stack-type piezoelectric actuators arranged in a rectangular grid. The faceplate is thick enough to embed monolithic cooling channels inside the faceplate in the next version. The faceplate without cooling channels presented in this paper has a high bending stiffness compared with glass DM's, and the proposed actuator configuration has a flexure support to reduce the shear stress at the adhesive while preserving optical performances. To examine the characteristics of the SiC DM, we simulated the influence functions (IFs) by using a finite element analysis (FEA) and then compared them with the IFs measured by using an optical interferometer. The IF describes the shape to which the mirror will deform when a voltage is applied to a single actuator. Using these IFs, we could estimate the command to make the final shape of the DM. Also, in order to verify bandwidth of the DM, we measured the response time of actuator and frequency response of the DM. The optical performance of the DM was verified by generating Zernike polynomials modes based on the IFs measured with the interferometer and by compensating arbitrarily distorted wavefront.

9909-292, Session PThu3

Research on the optimization of a bimorph piezoelectric deformable mirror-based on zeroth-order method

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The deformable mirror adjusts the mirror surface shape to compensate the wavefront error in the adaptive optics system. Recently, the adaptive optics has been widely used in many applications, such as astronomical telescopes, high power laser systems, etc. These applications require large diameter deformable mirrors with large stroke, high speed and low cost. Thus, the bimorph piezoelectric deformable mirror, which is a good match for the applications, has attracted more and more attentions. In this paper, we use zeroth-order optimization method to optimize the physical parameters of a bimorph piezoelectric deformable mirror that consists of a metal reflective layer deposited on the top of a slim piezoelectric ceramic surface layer. The electrodes are deposited on the bottom of the piezoelectric ceramic layer. The physical parameters to be optimized include the optimal thickness ratio between the piezoelectric layer and reflective layer, inter-electrode distance, and so on. A few reasonable designs are obtained by a comparative study presented for three geometries of electrodes, which are circular, square and pentagon, respectively.

9909-294, Session PThu3

Bimorph Mirrors for Adaptive Optics in Space Telescopes

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This paper considers the design of deformable mirrors to be used as wavefront correctors for space telescopes. These are intended to compensate for manufacturing errors, gravity release and thermal distortion affecting large lightweight, low-cost Aluminium primary mirrors. The mirror consists of a unimorph design actuated with an array of piezoelectric (PZT) actuators operating in the d31 mode.

The first part of the paper reviews the merit of various possible configurations proposed in the literature with respect to their thermal stability, natural frequency and control authority (deformation amplitude). Some new configurations are suggested.

The second part describes a demonstrator developed on behalf of ESA. It consists of a single-crystal Silicon wafer (D=75 mm t=500µm) actuated with a PZT actuator with 25 independent electrodes. It is mounted on an isostatic support that allows the control of the rigid-body motion (Figure 1). The PZT actuating layer is glued under electrical voltage, in order to allow to be operated with a constant bias (single sided operation, V>0). The keystone electrode pattern is done by laser ablation and is modified to include the feeding tracks, in such a way that the electrical connections are outside the pupil. This mirror has demonstrated the capability to control the first 15 Zernike modes with a RMS error < lambda nm in a pupil of 30 mm (< lambda/20 for lambda=633nm). The first natural frequency is 245 Hz. Environmental tests are under way.

9909-299, Session PThu3

Development of a compact space-capable deformable mirror controller

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Direct imaging exoplanet missions require a Starlight Suppression System (SSS) to observe exoplanets around nearby stars. An SSS that uses an internal coronagraph requires controlling the wavefront error level down to nanometer or even angstrom level to avoid starlight contamination or speckles.

With standard high-quality optics and a modern coronagraph such as the Phase Induced Amplitude Apodization (PIAA) contrasts are limited to 1x10-5 due to optics aberrations and alignment errors. To overcome this challenge current direct imaging exoplanet testbed demonstrators utilize a Deformable Mirror (DM) to correct manufacturing and alignment wave front errors. Deformable mirrors have allowed different facilities to reach record contrast levels of 1x10-8 in air at the NASA Ames laboratory and 1x10-9 in vacuum at JPL.

Modern coronagraph utilizes at least 1,000 actuators with strokes of ~2?m which for many DM designs results in 200V potentials to be applied and a resolution of at least 14bits over the voltage dynamic range. These requirements result in bulky, heavy and high power consumption DM controllers that are not suitable for space missions, especially small ones.

We present the development and test results of a compact space-capable DM controller that is able to control a BMC Kilo-DM with 14bit resolution over 250V dynamic range. The controller will fit in a 0.5U volume, weights 0.5kg, and consumes less than 10W. Such a controller will enable small space telescope missions utilizing coronagraphs and will retire important risks for larger missions.

9909-321, Session PThu3

Fault-tolerant drive electronics for a Xinetics deformable mirror at GeMS DM0

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Gemini South is replacing one of the (3) CILAS DMs with a 349-actuator Xinetics DM in its GeMS MCAO system. Xinetics mirrors operate over a 40-100V dynamic range and require that inter-actuator stroke differences are limited to half-scale; each actuator must be within 30V of its neighbor to prevent mechanical stress and possible face sheet separation. A robust way to implement this protection is to use high power transient voltage suppressors (TVSs) as a 2D-mesh between the amplifiers and mirror, but this has system implications. A sustained clamp condition dissipates significant power in the devices, and if an actuator fails as a short (which occurred once with the DM in a thermal chamber), the system is subject to a cascade failure event as multiple outputs drive the shorted actuator through the TVS network. This latter risk is readily resolved by using series fuses to the DM. In this third-generation driver, current sensing and logic inhibit amplifier outputs after a sustained TVS clamp condition or shorted output, and LED indicators show the location. Redundant thermal sensing is used on modular TVS row and column boards. A second 2D-mesh of high impedance resistors after the fuses will hold an unpowered channel to the average voltage of its neighbors, with a negligible influence function. A Failure Modes and Effects Analysis shows significant fault tolerance.

9909-58, Session 16

Review of the outer scale of the atmospheric turbulence *(Invited Paper)*

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Outer scale is a relevant parameter for the experimental performance evaluation of large telescopes. The actual size of the outer scale has long been controversial, with measured values ranging from less than 10 m to more than 2 km. What is not controversial is the conclusion that when the diameter of the telescope approaches or exceeds the size of the outer scale, the optical consequences of atmospheric turbulence are changed dramatically from their traditional Kolmogorov behavior. In particular, power in the lowest Zernike aberration modes, e.g., tip and tilt and the overall stroke required for an Adaptive Optics (AO) system can be much reduced. A finite outer scale has implications for interferometry as well. With the current interest in the design of extremely large ground-based optical and infrared telescopes, reliable estimates of the outer scale profile

have assumed considerable importance.

Different techniques have been used for the outer scale L0 estimation. In situ measurements with radio-balloons have given very small local L0. The outer scale has also been estimated directly at the ground from the wave-front analysis from High Angular Resolution (HAR) techniques using interferometric or Shack-Hartmann or more generally AO systems data. Dedicated instruments have been also developed for the outer scale monitoring such as the Generalized Seeing Monitor (GSM) and the Monitor of Outer Scale Profile (MOSP). The measured values of outer scale from HAR techniques, GSM and MOSP are somewhat coherent and are larger than the in-situ results. The main explanation of this difference comes from the definition of the outer scale itself.

This paper aims to give a review of different techniques and instruments for the measurement of the outer scale. Comparisons of outer scale measurements will be discussed in light of the different definitions of this parameter and the associated observable quantities.

9909-59, Session 16

Local turbulence and its influence on adaptive optics performance at the GREGOR solar telescope

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The images of ground-based astronomical telescopes operating in visible or infra-red wavelengths are affected by turbulence in the Earth's atmosphere which, at a good astronomical site, is concentrated to layers close to the ground in daytime conditions. The resulting image degradation affects the performance of adaptive optical systems and causes residual aberrations in the science focus which reduce the spatial resolution of solar observations. Additional sources of turbulence are heating of the infrastructure close to the telescope and obstructions to a free air flow which otherwise would improve local seeing. These effects are usually a big concern for telescope operations, but difficult to detect and to monitor. So far, there is little knowledge about local influence of the infrastructure on the image quality of a solar telescope.

The strength of optical turbulence is determined by the structure function parameter of the refractive index Cn2. We investigate the temporal behavior of the free flow turbulence at the telescope dome level through continuous measurements of Cn2 using a laser scintillometer between the towers of the Vacuum Tower Telescope and of GREGOR at the Teide observatory at Tenerife in the Canary Islands since September 2012. In addition, local measurements of Cn2 are being taken in the vicinity of the GREGOR telescope using three ultrasonic anemometers since May 2015. Two anemometers are located at the north and south ends of the telescope platform, a third one can be placed close to the telescope. The comparison of the results of the four instruments is presented and discussed. It appears that the mountain ridge effects on turbulence are more relevant than any local causes of seeing close to the telescope. We compare the results of the turbulence effects with image quality indicators collected by the adaptive optics system GAOS at the GREGOR telescope

9909-60, Session 16

Modeling and prediction of non-stationary optical turbulence behavior

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Optical turbulence parameters, such as seeing angle, outer scale, isoplanatic angle and coherence time show temporal variability. Modelling and prediction of the temporal behaviour of the parameters is essential for the following reasons:

(1) the efficient scheduling of scientific programs and use of astronomical instruments,

(2) the tuning of AO systems and instruments towards the actual atmospheric condition,

(3) the simulation of astronomical instrument's performance under time-varying turbulence.

Furthermore, turbulence modelling and prediction can be used to:

(4) improve the adaptive tracking performance of Linear Quadratic Gaussian (LQG)-type controllers, as LQG controllers need to be tuned towards the specific turbulence conditions.

We have analysed integrated turbulence data from the Stereo-SCIDAR instrument (Durham University), installed at the 2.54m INT telescope, La Palma (2014 and 2015). Before model fitting, the pre-processing of data is crucial, in particular regarding: the non-uniform sampling intervals, missing samples and the non-negative values. It has turned out that a fractionally integrated stochastic model gives an accurate description of the temporal behaviour of the integrated seeing angle over 18 nights of Stereo-SCIDAR observations.

Based on the characteristics of this stochastic model we can conclude that the time series of the seeing angle is non-stationary. This implies that the variance of the forecast error will a) increase with the prediction horizon and b) will diverge for long predictions horizons. Similar modelling and forecast results have been obtained for the isoplanatic angle and the coherence time from the Stereo-SCIDAR measurements at INT.

Moreover, using data from 9 observing nights of the Generalized Seeing Monitor (GSM) at Paranal (2007), we have found that the temporal evolution of the turbulence outer scale can be captured by a similar stochastic model. Outer scale modelling and forecasting is of particular interest to Extremely Large Telescopes.

The paper discusses the time series pre-processing, the modelling procedure and the impact on turbulence parameter forecasting.

9909-61, Session 16

E-ELT turbulence profiling with stereo-SCIDAR at Paranal

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Vertical profiles of the atmospheric optical turbulence strength and velocity is of critical importance for simulating, designing, and operating the next generation of instruments for the European Extremely Large Telescope. Many of these instruments are already well into the design phase, meaning these profiles are required immediately to ensure they are optimised for the unique conditions likely to be observed.

Stereo-SCIDAR is a generalised SCIDAR instrument which is used to characterise the profile of the atmospheric optical turbulence strength and wind velocity using triangulation between two stars. The data are analysed and made available to observatory systems in real-time. Stereo-SCIDAR has demonstrated the capability to resolve turbulent layers with the required vertical resolution to support wide-field ELT instrument designs. These high resolution atmospheric parameters are critical for design studies and statistical evaluation of on-sky performance under real conditions.

Here we report on the new Stereo-SCIDAR instrument installed on one of the Auxillary Telescope ports of the Very Large Telescope array at Cerro Paranal. Paranal is located approximately 20 km from Cerro Armazones, the site of the E-ELT. Although the surface layer of the turbulence will

be different for the two sites due to local geography, the high-altitude resolution profiles of the free atmosphere from this instrument will be the most accurate available for the E-ELT site.

In addition, these independent profiles can also be used to further characterise the site of the VLT. This can enable instrument performance calibration, optimisation and data analysis of, for example, the ESO Adaptive Optics facility and the Next Generation Transit Survey. It will also be used to validate atmospheric models for turbulence forecasting.

We show early results from the commissioning of the instrument and address future implications of the results.

9909-62, Session 17

The AIROPA software package: milestones for testing general relativity in the strong gravity regime with adaptive optics

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Adaptive optics (AO) near-infrared observation with NIRC2 @ Keck II has enabled us to monitor stellar orbits in the innermost arcsecond of the Galactic Center (GC), and led to the detection of the supermassive black hole and many unexpected findings about its environment. With almost two decades of data, continuing this experiment will allow us to test General Relativity in the strong-gravity regime starting in 2018. Our data analysis tool of choice is the IDL point spread function (PSF) fitting package, StarFinder, for extracting precise astrometry and photometry (Diolaiti et al. 2000). However, StarFinder does not fully account for the spatial variability of the PSF due to atmospheric anisoplanatism and instrumental aberrations as seen in NIRC2 images. Recently, it became evident that spatial variability of the PSF is one of the major sources of our remaining systematic uncertainty in AO astrometry and photometry.

The Galactic Center Group @ UCLA is in the final year of a project in which we have developed algorithms to predict how the PSF varies and incorporated them into a new software package: AIROPA (Anisoplanatic and Instrumental Reconstruction of Off-axis PSFs for AO). This software package makes use of independently measured atmospheric turbulence profiles and predicts the differential OTFs between different field positions. Based on ARROYO (M. Britton 2006), a set of C++ class libraries that aim to support simulations of electromagnetic wave propagation through turbulence and through optical systems, AIROPA includes C++ tools for predicting both natural guide star and laser guide star PSFs, as well as application program interfaces (APIs) for IDL. Furthermore, it provides an extensive set of IDL modules for Fourier-based PSF manipulation and for PSF modeling from any externally generated aberration maps. These IDL routines and APIs are integrated with a modified version of StarFinder.

In order to characterize the instrumental aberrations of NIRC2 we derived phase maps as a function of detector position from phase diversity measurements. These measurements show a differential wavefront error up to 220 nm across the detector. A detailed model of the instrumental PSF variability and its stability over time was developed. In order to make use of the new software in the context of astrometric measurements, a new distortion map for NIRC2 was derived from recent observations.

AIROPA configuration files provide easy adaptation to NIR instruments other than NIRC2. In this talk we present the summary of our project and the key developments that we intend to disseminate. We demonstrate that AIROPA predicts the observed differences in Strehl-ratio of up to ~5% under typical GC conditions in K-band (~10% in H-band) reliably, reduces PSF residuals by at least a factor of three in comparison to single-PSF analysis, and delivers more precise astrometry and photometry for stellar orbits at the Galactic Center and other NIRC2 projects. It is a milestone on the way to the measurements of general relativistic effects on stellar orbits.

9909-63, Session 17

Point spread function determination for Keck adaptive optics

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W. M. Keck Observatory (WMKO) was the first to implement both natural guide star (NGS) and laser guide star (LGS) AO systems on a large telescope in order to achieve angular resolutions in the near-infrared that match the capabilities of the Hubble Space Telescope in the visible. Over 600 refereed science papers have been produced using the Keck AO systems. In addition to providing the first NGS and LGS AO facilities on a large telescope, WMKO has endeavored to continually improve the capabilities of these systems.

One of the primary scientific limitations of AO has been the incomplete knowledge of the point spread function (PSF), which has made it difficult to use AO for accurate photometry and astrometry in both crowded and sparse fields, for extracting intrinsic morphologies and spatially resolved kinematics, and for detecting faint sources in the presence of brighter sources. To address this we initiated a program to determine and demonstrate PSF determination for science observations obtained with Keck AO. The goal is to provide a PSF estimate for every point in the science field. The resulting capability of producing a high-fidelity PSF estimate will provide dramatic science gains and stands as one of the next major challenges for achieving further breakthroughs in high angular resolution science. This paper aims to give a broad view of the progress achieved in implementing this capability for Keck AO science observations.

The concept and the implementation are briefly described. Our approach involves (1) computing the guide star PSF from wave front sensor (WFS) measurements using the technique introduced by Jean-Pierre Véran et al. (1997), (2) determining low order aberrations that are apparently unseen by the wavefront sensor using on-sky phase diversity, and (3) computing the science PSF by applying anisoplanatic corrections to the guide star PSF using a modified version of the Arroyo software package written by Matthew Britton (2015).

The design and development of operational tools for automated PSF reconstruction is presented along with the latest on-sky results using the NIRC2 science instrument. The operational tool kit includes a database and data management tools to handle large volume of AO telemetry data and facilitate multitasking across multiple computers on the network.

On-sky performance of the technique is discussed by comparing the Strehl ratio and the full with half maximum (FWHM) of the reconstructed PSFs to that of the NIRC2 PSFs. Initial results from shared-risk science verification are also presented.

Results from a trade-off study comparing two sets of software tools for

atmospheric seeing estimation and non-common path static aberrations (one developed at the WMKO and the other at University of Applied Sciences Western Switzerland) are presented. The statistics on seeing conditions and telescope/AO performance over a two year period are also presented along with their impact on contributions from the individual PSF reconstruction error terms. The statistical results are discussed in the context of AO science with the current and future optical telescopes and instruments. The PSF algorithm development for this program is presented in a separate paper.

9909-64, Session 17

MOAO PSF reonstruction validated using on-sky CANARY data

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We discuss a Real Time Computer (RTC)-based point spread function reconstruction (PSFR) algorithm for Laser Guide Stars (LGS)-assisted tomographic AO systems. Our approach consists in retrieving relevant system and turbulence parameters, as the seeing, layer strengths, outer scale and wind speed profiles. We then derive covariance matrices and pupil-averaged phase structure functions to get stationary Optical Transfer Functions (OTF) and thereupon PSFs.

The algorithm is a generalization of the error breakdown proposed for the MOAO pathfinder Canary developed by LESIA and Durham University: the residual OTF is split into a product of several OTFs, each representative of an error term. We describe how each of these OTFs is determined and their variation as a function of the inputs provided by the RTC.

Based on the post-processing of a large amount of on-sky data we show statistics of the PSFR and demonstrate our ability to reliably reconstruct the PSF.

The prospects of scaling this approach to ELTs, in particular in the context of the Harmoni project are also considered.

9909-65, Session 17

Exploiting physical constraints for multi-spectral exoplanet detection

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The residual speckles due to the host star set the most serious limitation in the detection of exo-planets in high contrast coronographic images provided by instruments such as SPHERE or GPI. Instead of working on image differences, we propose to tackle the exo-planet detection as an inverse problem where the residual speckles and the exo-planet parameters (position and spectrum) are jointly estimated from a set of multi-spectral images and, possibly, multiple exposures. In order to reduce the number of degrees of freedom, we impose specific constraints on the spatio-spectral distribution of stellar speckles. These constraints are deduced from the multi-spectral Taylor series expansion of the diffraction pattern for an on-axis source which implies that the speckles are a combination of spatial modes with deterministic chromatic magnification and weighting. We show how a practical way to solve the difficult problem of joint estimation of all the parameters given the data. For instance, the non-trivial problem of the estimation of the spatial modes and the spectral weights is solved by a low-rank approximation method. Thanks to the physically motivated constraints on the stellar leakage, optimal speckle suppression is achieved without the need to introduce additional heuristic parameters. As a by-product, our approach yields the maximum likelihood estimator of the planet spectral energy distribution (SED) and its covariance. The proposed method is versatile and can take into account any kind of multi-variate data. We present results based on both simulated and real data from the integral field spectrograph of SPHERE.

9909-66, Session 17

Measurement and correction of distortion for optimal image stacking in wide-field multi-conjugate adaptive optics: application to GeMS data

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The advent of a new generation of Wide Field Adaptive Optics (WFAO) systems marks the beginning of a new era in high spatial resolution imaging. By using multiple Laser Guide Stars (LGS), WFAO significantly increases the field of view of the AO-corrected images, and the fraction of the sky that can benefit from such correction. The newly commissioned Gemini South Multi-Conjugate Adaptive Optics System (GeMS) combined with the infrared camera GSAOI is delivering almost diffraction- limited images over a field of ? 2 arc-minutes across. However, despite the excellent performance of the GeMS/GSAOI system, the correction provided is not perfectly uniform and may generate variable Point Spread Function (PSF) over the field. The ability to deal with those PSF variation is critical for high-precision astrometry and photometry studies. In a first part of this paper we expose the existing photometric tools, their performance and limitations. We also present upgrades implemented using the current photometric tool STARFINDER to adapt it to variable PSF over the field of view. This analysis is done using simulated as well as on sky data obtained with the GeMS/GSAOI system : a recent observations of a very active and young star-forming region N-159W located in the Large Magellanic Cloud. We obtained deep J,H, and Ks images in order to study the properties of the cluster stellar members and bring new elements to our understanding of the massive star formation process. In a second part of this paper, we pay attention to a phenomena that critically amplify the PFS variation over the field and can strongly degrade the resolution and reduce the sensitivity when combining multiple frames : the optical distortion introduced by the optical components present in the telescope and the instruments. In particular, GSAOI is severely affected by static and quasi-static distortion that may vary from one frame to another. We investigate here, an optimal way to correct for the distortion following an inverse problem approach based on the work presented in Gratadour et al. (Astron. Astrophys., 443 :357–365, November 2005.) on image re-centering, but generalized to all distortion modes. In this paper we present the formalism as well as simulation results. We also show first application on real data and we confront our method with existing tools.

9909-67, Session 18

The GMT active and adaptive optics control strategies

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The Giant Magellan Telescope (GMT) has a Gregorian 25.4-meter diameter primary mirror composed of seven 8.4-meter diameter segments.

The secondary mirror consists of seven 1.1-meter diameter segments.

In the active and adaptive operation modes of the GMT, around a dozen wavefront sensors are selectively used to monitor the optical aberrations across the focal plane.

A dedicated wavefront control system drives slow and fast corrections at the M1 and M2 mirrors to deliver image quality optimized for the field of view of the scientific instrument in use.

This paper describes the control strategies for the active and adaptive optics modes of the GMT.

Different wavefront estimation algorithm are compared and the performance of the GMT, in the different observing modes, is evaluated using the Dynamic Optical Simulation package.

9909-68, Session 18

AOF laser tomography mode: reconstruction strategy and first test results

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GALACSI is the Adaptive Optics (AO) system serving the instrument MUSE in the framework of the Adaptive Optics Facility (AOF) project. GALACSI offers two AO correction modes:

- The Wide Field Mode (WFM) is a Ground Layer AO (GLAO) mode delivering a homogeneous PSF across a FoV of 1' diameter. The results obtained during the WFM system tests are described in another paper at this conference (J. Kolb et al.)

- The Narrow Field Mode (NFM) is a Laser Tomography AO (LTAO) mode delivering high resolution in the visible across a small FoV of 7.5" diameter around the optical axis.

GALASCI NFM relies mostly on the same main subsystems as the WFM, i.e. a Deformable Secondary Mirror (DSM) with 1156 voice coil actuators in the pupil, controlled by 4 Laser Guide Star (LGS) Shack-Hartmann (SH) Wave Front Sensors (WFS) composed of 40x40 subapertures of 6x6 pixels, via the Real Time Computer (RTC) SPARTA. The main difference with respect to the WFM comes from the fact that instead of a simple visible Tip/Tilt sensor, GALACSI NFM makes use of a Low Order (LO) Natural Guide Star (NGS) loop correcting Tip/Tilt and Defocus thanks to an InfraRed (IR) 2x2 SH-WFS. An adaptive vibration tracking algorithm is applied along these three modes to cancel vibrations whose frequency is higher than the AO correction bandwidth.

From a reconstruction standpoint, GALACSI NFM intends to optimize the correction on axis by estimating the turbulence in volume via a tomographic process, then projecting the turbulence profile onto one single DM located in the pupil, close to the ground.

In this paper, the laser tomographic reconstruction process will be described. Several methods (virtual DM, projection method) will be studied, under the constraint of a single matrix vector multiplication. The LTAO interaction matrix model design will be analysed and the reconstruction parameter space will be explored, in particular the number of reconstructed layers and the regularization terms.

Furthermore, we will present the strategy to define the controlled modal basis and split the control between the LO loop and the HO loop.

Finally, closed loop performance obtained with a 3D turbulence generator on the ASSIST test bench will be analysed with respect to the most relevant system parameters to be tuned.

9909-69, Session 18

Fast tomographic reconstructors for ELT-sized wide field of view AO systems

Ronny Ramlau, Daniela Saxenhuber, Johannes Kepler Univ. Linz (Austria); Roland Wagner, Johann Radon Institute for Computational and Applied Mathematics (Austria)

Wide field of view Adaptive Optics (AO) systems, such as Multi-Conjugate Adaptive Optics (MCAO), Laser Tomography AO (LTAO) and Multi-Object AO (MOAO), require an accurate reconstruction of the turbulent atmosphere in order to obtain a good correction over a large field of view. For the upcoming generation of Extremely Large Telescopes (ELT), with mirror diameters of up to 40m, this involves the solution of huge systems under restrictive time constraints. Therefore, fast reconstruction algorithms for atmospheric tomography are needed.

In this talk, we analyze the problem of atmospheric tomography, review and study the performance of fast iterative methods, such as the wavelets based FEWHA (Finite-Wavelet Hybrid Algorithm), the Gradient-based method and the Kaczmarz algorithm. All of these iterative algorithms solve the tomography problem in a functional setting, i.e. without any matrix-vector-multiplication. Thus, they scale linearly with the number of unknowns, and exhibit superior speed performance.

Furthermore, we present several new approaches for improvements in the field of atmospheric tomography: In the context of MCAO, a combined approach for PSF reconstruction throughout atmospheric tomography is described along with a new algorithm for the DM fitting step.

Our PSF reconstruction algorithm combines existing, verified techniques in a novel way to deliver accurate field dependent PSFs in very short time.

Novel approaches for cost reduction via compression of the reconstruction profile before as well as during tomography itself are presented. On the one hand this consists of a compression algorithm to determine the optimal reconstruction profile from a given atmospheric model. On the other hand, a joint optimization of tomographic reconstruction and layer profile that serves as model reduction is presented.

Our simulation results are obtained on OCTOPUS, the ESO end-to-end simulation tool. For a variety of atmosphere and system parameters, they suggest a good qualitative performance along with a considerable reduction of computational effort.

9909-70, Session 18

20 kHz real-time control system for adaptive optics

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GPU-based systems have become the standard for low latency adaptive optics real-time control systems. While GPU systems are able to meet latency requirements of many instruments in operation today, they are limited in their processing capability by two factors: the lack of GPU support for application-level direct access to PCI Express and the absence

of frame grabbers with application-tuned DMA transfer size capability. We present here a multi-DSP based real-time control system for adaptive optics that leverages on the PCI Express multicast capability and DMA-tuned frame grabbers to deliver processing rates in excess of 20 kHz and a latency in single-digit microsecond range for 56x64 pixel frames.

9909-71, Session 19

NGS2: a focal plane array upgrade for the GeMS multiple tip-tilt wavefront sensor

Francois Rigaut, Francis Bennet, Ian Price, The Australian National Univ. (Australia); Vincent Garrel, Gemini Observatory (Chile); Celine d'Orgeville, Research School of Astronomy & Astrophysics (Australia); Chadwick A. Trujillo, Vanessa Montes, Gemini Observatory (Chile)

GeMS, the Gemini Multi-Conjugate Adaptive Optics System, is currently using an Avalanche Photo Diode (APD) based Natural Guide Star Wavefront Sensor (NGSWFS). APDs are well suited to the low counts generally dealt with, but unfortunately they are rather bulky and difficult to integrate into optics. The current NGSWFS is using a rather complex optical design, with pyramids in the focal plane, feeding the light to fibres, that transmit it to the APD themselves. Optical component are tiny, and very difficult to align. The current optical throughput has been measured to be around 4%, reducing drastically the sensitivity of the NGSWFS and impacting directly GeMS sky coverage (around 6% instead of the 30% initially specified). We will present NGS2, an upgrade for the GeMS NGSWFS based on a single focal plane array, from which up to three Regions of Interest (ROIs) are read. NGS2 is using a Nuvu HNu512 EMCCD detector, the first available high sensitivity science array available with multiple ROI capability, providing frame rate of up to 800Hz with three 8x8 pixel windows. We will report on the design, detector characterisation, system performance, as well as on sky results, if available. We will also discuss the advantages and challenges of this type of focal plane array design compared with more conventional design (e.g. the current APD-based multiple guide probe design), in light of sensitivity, operational and astrometric considerations.

9909-72, Session 19

Validation of tomographic laser guide star uplink tip-tilt determination with CANARY

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Laser Guide Stars (LGS) have greatly increased the sky-coverage of Adaptive Optics (AO) systems, but due to the up-link turbulence experienced by LGSs, a Natural Guide Star (NGS) is still required for tip-tilt correction. This limits sky-coverage to areas where bright NGS are available. For many scientifically interesting areas of the sky, this is not the case, curtailing the impact of ground based astronomy. A method has recently been presented which promises to determine the LGS uplink tip-tilt in tomographic LGS AO systems by using the fact that each LGS Wave Front Sensor (WFS) in a tomographic AO system observes the uplink path of other LGSs. It has been shown through simulation that tip-tilt information from high altitude turbulence can be determined from LGS alone leaving only contributions from turbulence near the ground. As low altitude turbulence is common to a large field, it is then possible to use NGS further from the science target to obtain the remaining tip-tilt information. Such a technique has the potential to greatly increase the sky-coverage of Multi-Object, Laser Tomographic and Multi-Conjugate AO systems by allowing further off-axis NGS tip-tilt stars to be used for correction. For certain low spatial resolution scientific applications, it may even allow the entire sky to be observed with no tip-tilt NGS.

Here, we summarise the LGS tip-tilt retrieval method and show results from simulation that show the determination of high altitude tip-tilt. The increase in allowed off-axis tip-tilt NGS position is estimated, and thus the increase in sky coverage of tomographic AO systems. We also assess the performance of tomographic LGS AO systems with no tip-tilt NGS correction. Previously, the method required simulated covariance matrices to form a LGS tip-tilt retrieving tomographic reconstructor, which would not be practical to create for real AO systems. An analytical approach to creating those matrices, where LGS uplink turbulence is included, is described, allowing a "Learn and Apply" type approach to be followed, opening the algorithm for use with on-sky AO systems. We finally present analysis of open loop wave front sensor data from the CANARY Multi-Object AO demonstrator, which features four LGS in a tomographic configuration, with an on-axis "truth" WFS observing in the direction of a science target. This analysis validates that the technique works with on-sky AO systems.

9909-73, Session 19

Anti-aliasing optical method for Shack Hartmann WFSs

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Measurement errors due to aliasing in a Shack-Hartmann WFS are typically 40% larger in variance than the fitting error of an AO system. On bright stars, aliasing is the dominant error within the control radius of the deformable mirror. Wavefront spatial frequencies beyond the WFS' Nyquist frequency corrupt measurements below this frequency. A common misconception is to think that aliasing primarily affects the higher spatial frequency measurements. But in fact aliasing propagates to the lowest order modes, and corrupts even tip/tilt. There are many examples including the observation that the temporal power spectrum of measured tip/tilt from a WFS does not correspond to Kolmogorov theory. We propose a simple optical modification to a SH WFS (borrowed from the digital video camera industry), and present simulation results showing that the aliasing errors are dramatically reduced.

9909-74, Session 19

The QACITS pointing sensor: from theory to on-sky operation on Keck/NIRC2

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Small inner working angle coronagraphs are essential to benefit from the full potential of large and future extremely large ground-based telescopes, especially in the context of the detection and characterization of exoplanets. Among existing solutions, the vortex coronagraph, and in particular the AGPM (Annular Groove Phase Mask, a sub-wavelength

grating creating a vortex phase of charge 2), stands amongst the most effective and promising solution. However, a small inner working angle comes necessarily with a high sensitivity to pointing errors. This is the reason why a pointing control system is imperative to stabilize the star on the vortex center against pointing drifts due to mechanical flexures, that generally occur during observation due for instance to temperature variations.

We have therefore developed a technique called QACITS (Quadrant Analysis of Coronagraphic Images for Tip-tilt Sensing), which is based on the analysis of the coronagraphic image shape to infer the amount of pointing error. We show that the flux gradient in the image is directly related to the amount of tip-tilt affecting the beam. The main advantage of this technique is that it is does not require any additional setup and it can thus be easily implemented on all current facilities equipped with a vortex phase mask.

In this presentation, we will introduce the theoretical model we have derived to predict the shape of the image in presence of low-order aberrations in a vortex coronagraph. For that purpose, we have based our computations on Zernike formalism. This basis has turned to be very convenient to derive the effect of a vortex phase on small aberrations. The results of these developments can be summarized with an aberration conversion table between the entrance and exit pupil (Lyot) of the coronagraph. For instance, a given tip-tilt mode is redistributed onto both tip-tilt modes after the coronagraph, while a defocus aberration is turned into astigmatism, and conversely, astigmatism is turned into defocus.

Finally, we will present our latest results obtained with an L-band AGPM commissioned at Keck/NIRC2 in June and October 2015, validating the theoretical model on-sky. A close-loop correction was implemented and successfully tested on-sky, in conjunction with a speckle nulling correction. The algorithm operates in three steps: flux and background calibration, alignment optimization and science acquisition sequence. It has been designed to be easily handled by any user observing in vortex mode. We show that the QACITS algorithm stabilizes the star down to 0.027 lambda/D (2mas) rms in average, and down to 0.013 lambda/D (1mas) rms in the best cases. This pointing sensor is mainly correcting for drifts that affect the beam at the rate of up to 0.04 lambda/D per mn, while the speckle nulling map was correcting for quasi-static aberrations. To conclude, we will present the contrast curve achieved with this correction.

9909-75, Session 19

The coronagraphic modal wavefront sensor: focal-plane sensing for high-contrast imaging

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Non-Common Path Errors (NCPEs) are one of the dominant factors limiting the performance of current astronomical high-contrast imaging instruments. If uncorrected, the resulting quasi-static speckle noise floor limits the achievable raw contrast to typically 10-3-10-4, a value which does not improve with increasing integration time.

The coronagraphic Modal Wavefront Sensor (cMWS) is a hybrid phase optic which uses holographic PSF copies to supply focal-plane wavefront sensing information directly to the science camera, whilst also maintaining a bias-free coronagraphic PSF. The initial concept has been successfully implemented on-sky at the William Herschel Telescope (WHT), La Palma (Wilby et al., in prep.), demonstrating both real-time wavefront sensing capability and successful extraction of slowly varying wavefront errors under a dominant and rapidly changing atmospheric speckle foreground.

In this work we present an optimised cMWS capable of efficient NCPE correction using only a limited number of tailored sensing modes. We assess sensor performance under realistic observing conditions, pending on-sky closed-loop testing with the Leiden Adaptive Optics Testbed at the WHT.

Conference 9910: Observatory Operations: Strategies, Processes, and Systems VI

SPIE. ASTRONOMICAL TELESCOPES + INSTRUMENTATION

Monday - Friday 27–1 July 2016

Part of Proceedings of SPIE Vol. 9910 Observatory Operations: Strategies, Processes, and Systems VI

9910-1, Session 1

Operational metrics for the ESO Very Large Telescope: lessons learned and future steps

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When ESO's Very Large Telescope started its operations in April 1999 it was the first ground-based facility to offer to the scientific community at large access to an 8-10m class telescope with both classical and queue observing. The latter was considered to be the most promising way to ensure the observing flexibility necessary to execute the most demanding scientific programmes under the required, usually very well defined, conditions.

Since then new instruments have become operational and 1st generation ones replaced, filling the 12 VLT foci and feeding the VLT Interferometer and its four Auxiliary Telescopes. Efficiently operating such a broad range of instruments installed and available every night of the year on four 8-metre telescopes offers many challenges. Although it may appear that little has changed since 1999, the underlying VLT operational model has evolved in order to accommodate different requirements from the User Community and features of new instruments.

Did it fulfil its original goal and, if so, how well? How did it evolve? What are the lessons learned after more than 15 years of operations? A careful analysis and monitoring of statistics and trends in Phase 1 and Phase 2 has been deployed under the DOME (Dashboard for Operational Metrics at ESO) project. The main goal of DOME is to provide robust metrics that can be followed with time in a user-friendly manner. Here, we summarize the main findings on the handling of service mode observations and present the most recent developments.

9910-2, Session 1

The impact of science operations on science return at the Very Large Telescope

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The operational implementation of observing programmes influences the scientific return of an Observatory. More than 15 years of observations with the VLT/Paranal Observatory allow us to assess the impact of science operations and programme implementation on its scientific performance. Bibliometric parameters are used to derive programme productivities and their relation to scheduling implementation (such as service and visitor mode) and programme types.

In this contribution we present a set of performance indicators comparing specific programme implementation and execution parameters.

Results of this analysis help us to identify strengths and weaknesses of the operational model adopted. It may entail improvements for an integrated VLT and ELT operations scheme in the next decade.

9910-3, Session 1

Improving SALT productivity by applying the theory of constraints

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SALT, the Southern African Large Telescope, is a very cost effective 10 m class telescope. This statement is based on its low initial capital investment and annual operating cost. The cost per refereed science paper is currently in the order of $70,000 (based on 32 papers published in 2015).

To achieve this competitive advantage, specific design trade-offs had to be made. The biggest constraint is the fact that the telescope structure is fixed in elevation, at 37 degrees from the zenith. The movable tracker provides ± 6 degrees deviation from the fixed elevation. This constraint restricts the observation annulus from -43 degrees to -31 degrees from the zenith. Despite these constraints, the fully queue-scheduled telescope can observe more than 70% of the sky available from Sutherland.

On the other hand, the telescope has many advantages, such as being able to switch between different instruments and observing modes during the night.

The SALT Operations team (integrated astronomy and technical teams) applied the principles of the theory of constraints to review the entire "science generation" process. The Theory of Constraints, by Dr. Eliyahu M. Goldratt, is a well-known and widely applied industrial engineering technique used to improve the productivity of a manufacturing or similar processes. Our goal was to identify how more observations could be done with the telescope and its instruments in its current configuration without spending large amounts of money on modifications and upgrade projects. Constraints were identified throughout the process starting from the PIs program proposals to their Time Allocation Committees (TACs), through to published refereed papers.

A 5-point plan was developed to address constraints:

1. Better interaction with PIs and TACs to advise them of how to achieve better results by taking into account telescope and instrument advantages and limitations.

2. Better simulation and scheduling tools. Simulating the probabilities of observing Priority 0 to P4 targets during the semester. This simulation determines what and how many programs could be completed during the semester. Another tool calculates the probability of observing a specific target during the semester. A scoring algorithm helps the astronomer to make optimised observation decisions during the night despite rapidly changing weather, humidity and seeing conditions.

3. Prioritized projects aimed at yielding better data quality and

productivity. These projects are beyond the scope of this paper but typically include the new edge sensor system for the primary mirror (SAMS). This system will reduce downtime and improve image quality.

4. Dashboard and Fault Tracking System to measure contracted metrics. They include for example, science time, number of observations, downtime, faulty, etc. and numbers of refereed papers published. The fault tracker provides details and durations of sub-systems causing downtime.

5. Interacting with PIs regarding the status of their data and helping them to process the data, if required, to publish refereed papers.

This 5-point plan resulted in better synergy, focus and coordination of the SALT Operations team. The end result is that the previous record number of observations per semester was beaten by 16%.

9910-4, Session 1

A bibliometric analysis of observatory publications for the period 2009-2013

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The primary scientific output from an astronomical telescope is the collection of papers published in refereed journals. A telescope's productivity is measured by the number of papers published which are based upon data taken with the telescope. The scientific impact of a paper can be measured quantitatively by the number of citations that the paper receives. In this paper I will examine the productivity and impact of over 25 telescopes, optical/IR, radio and space-based, for the years between 2009 and 2013.

9910-5, Session 1

Observatory bibliographies: an important resource in operating an observatory

Sherry L. Winkelman, Arnold H. Rots, Smithsonian Astrophysical Observatory (United States)

The Chandra Data Archive (CDA) maintains an extensive observatory bibliography. By linking the published articles with the individual datasets analyzed in the paper, we have the opportunity to join the bibliographic metadata (including keywords, subjects, objects, data references from other observatories, etc.) with the metadata associated with the observational datasets. This rich body of information is ripe for far more sophisticated data mining than the two repositories (publications and data) would afford individually. Throughout the course of the mission the CDA has investigated numerous questions regarding the impact of specific types of Chandra programs such as the relative science impact of GTO, GO, and DDT programs or observing, archive, and theory programs. Most recently the Chandra bibliography was used to assess the impact of programs based on the size of the program to examine whether the dividing line between standard and large projects should be changed and whether another round of X-ray Visionary Programs should be offered. Traditionally we have grouped observations by proposal. For this investigation we aggregated observations by pointing and instrument configuration such that objects observed multiple times in the mission were considered single observing programs. This change in perspective has given us new ideas for assessing the science impact of Chandra and for presenting data to our users. In this paper we present the methodologies used in the recent study, some of its results, and most importantly some unexpected insights into assessing the science impact of an observatory.

This work is supported by NASA contract NAS8-03060.

9910-6, Session 2

Data products in the ALMA and NRAO archives

Mark D. Lacy, National Radio Astronomy Observatory (United States)

The increasing size and complexity of radio astronomical datasets has resulted in demand for fully reduced data products (image cubes) to be made available to the user community from observatory archives. This is important both to allow novice users who have little radio astronomy experience to use these new facilties and for more experienced scientists to be able to quickly assess the quality of their datasets and speed up their analyses. This new requirement presents challenges of generation, storage and server-side visualization and analysis of very large datacubes. In this paper we estimate the relative size of data products and raw data as a function of observational parameters, plans for user-initiated reprocessing of data in the ALMA and NRAO archives (in addition to a default pipeline execution) and a discussion of future tools for remote visualization and analysis.

We also discuss the general implications for the design of future astronomical archives as we move away from the concept of an archive for storage and retrieval only into one that can also function as a portal for server-side data analysis.

9910-7, Session 2

Validation of ESO Phase 3 data submissions

Nausicaa A. R. Delmotte, Magda Arnaboldi, Stephan Geier, Laura Mascetti, Alberto Micol, Joerg Retzlaff, European Southern Observatory (Germany)

The data validation phase is an essential step of the Phase 3 process at ESO that is defining and providing an infrastructure to deal with interactions between the data producers and the archive. We are using a controlled process to systematically review all Phase 3 data submissions to ensure a homogeneous and consistent science archive with well traceable and characterised data products, to the benefits of archive users.

How the Phase 3 data validation plan is defined, and how its results are subsequently managed will be described in the presentation.

[For a description of its technical implementation, please refer to the submitted contribution by L. Mascetti.]

9910-8, Session 2

Publication of science data products through the ESO archive: lessons learned and future evolution

Joerg Retzlaff, Magda Arnaboldi, Nausicaa A. R. Delmotte, Laura Mascetti, Alberto Micol, European Southern Observatory (Germany)

Phase 3 denotes the process of preparation, submission, validation and ingestion of science data products for storage in the ESO Science Archive Facility and subsequent publication to the scientific community. In this paper we will review more than four years of Phase 3 operations at ESO and we will discuss the future evolution of the Phase 3 system.

9910-9, Session 2

The TESS science data archive

Daryl A. Swade, Space Telescope Science Institute (United States); Cory Heiges, General Dynamics (United States); Jon M. Jenkins, NASA Ames Research Ctr. (United States); David W. Latham, Harvard-Smithsonian Ctr. for Astrophysics (United States); Sean D. McCauliff, NASA Ames Research Ctr. (United States); Edward H. Morgan, MIT Kavli Institute for Astrophysics and Space Research (United States); William B. Sparks, Space Telescope Science Institute (United States); Roland Vanderspek, Massachusetts Institute of Technology (United States)

The Transiting Exoplanet Survey Satellite (TESS) is a survey mission designed to discover exoplanets around the nearest and brightest stars. TESS has been selected by NASA as an Astrophysics Explorer mission with a scheduled launch in August 2017. The Mikulski Archives for Space Telescopes (MAST) at the Space Telescope Science Institute (STScI) will serve as the archive for TESS science data.

TESS will conduct large area surveys of bright stars and known M dwarfs within about 60 parsecs. TESS will observe a single 24 degree by 96 degree sector of the sky for approximately 27 days before pointing to a new sector, surveying the entire sky over the two year prime mission.

Science data are captured in two observation types: Target Data and Full Frame Images. Target Data result from a subarray of pixels read out with a two-minute cadence from approximately 25,000 stars per sector. Target stars change every sector, but targets near the ecliptic poles may be observed in multiple sectors. The entire field of view is captured in Full Frame Images taken at thirty-minute cadence. Full Frame Images provide a rich source of high time resolution data for many astronomical investigations.

Archive data products originate from multiple elements within the TESS ground segment. The Payload Operations Center provides the archive with raw data from the spacecraft, operational files, and focal plane characterization models. The Science Processing Operations Center pipeline generates FITS files for the Target Data and Full Frame Images. Light Curves and Centroids are extracted from the Target Data. Threshold Crossing Events are identified from the Light Curves in the Transiting Planet Search pipeline and Data Validation Reports are generated. MAST will stage catalog data generated by the TESS Science Office (TSO). The TESS Input Catalog contains approximately half a billion objects that are potential TESS targets or may influence the photometry of TESS targets. The TESS Objects of Interest Catalog lists planetary candidates identified as Threshold Crossing Events. In addition, the TSO will manage the TESS Follow-up Observing Program in which ground and space based telescope will be used for follow-up observations of TESS Objects of Interest. Follow-up Observing Program participants will be responsible for submission of follow-up data to MAST.

The services provided by MAST for the TESS mission are to store science data and provide an Archive User Interface for data documentation, search, and retrieval. Target Data and Full Frame Images are expected to be available in MAST within two months after conclusion of a sector's data collection. Current estimates have 38 Terabytes of TESS data available through MAST for each year of the mission.

The MAST architecture is designed to support multiple missions. MAST currently serves data from the Hubble Space Telescope, Kepler, and approximately ten other missions, as well as numerous additional high-level science data products. MAST will be the JWST data archive. The TESS mission takes advantage of this multi-mission architecture to provide a cost effective archive that allows integration of TESS data with data from other missions.

9910-10, Session 3

Providing comprehensive and consistent access to astronomical observatory archive data: the NASA archive model

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Since the turn of the millennium a constant concern of astronomical archives has been providing data to the public through standardized protocols unifying data from disparate physical sources and wavebands across the electromagnetic spectrum into an astronomical virtual observatory (VO). In October 2014, NASA began support for the NASA Astronomical Virtual Observatories (NAVO) program to coordinate the efforts of NASA astronomy archives in providing data to users through implementation of protocols agreed within the International Virtual Observatory Alliance (IVOA). While NAVO directly funds efforts at the HEASARC, IRSA, MAST and NED, other NASA projects, in particular the Chandra Data Archive and the ADS are also active in the VO arena and actively coordinate their activities with NAVO as part of the NASA Astronomy Data Centers Executive Committee (ADEC) . These NASA archives and projects maintain key VO infrastructure in the US and are members of the US Virtual Observatory Alliance (USVOA). The USVOA is the national coordination body, which represents the US VO activities in the IVOA. Together with the NASA archives, it also includes the AAS community at large, providing a forum for VO discussion and activities representative of all branches of US astronomy including ground-based observatories and data centers to ensure that the US community is fully engaged in the VO process.

Over the past decade the number of protocols agreed by the IVOA has swelled to over 40 agreed upon technical standards with another 10 or so in various stages of development. Many of these standards have optional capabilities and some have gone through multiple versions during their development.

A major goal of the USVOA and in particular the NASA ADEC and NAVO collaboration has been to assess the available IVOA standards and define what the appropriate presence for the US and NASA astronomy archives in the VO should be. This includes evaluating what optional capabilities in the standards need to be supported, the specific versions of standards that should be used, and returning feedback to the IVOA, to support modifications if needed.

The NAVO collaboration has defined a basic model and are now implementing capabilities. Our standard model provides for discovery of resources through the VO registries, access to observation and object data, downloads of image and spectral data and general access to archival datasets. Specific protocol versions have been chosen, minimum capabilities defined, and all dependencies have been identified. The model will evolve as the capabilities of the virtual observatory and needs of the community change. The other NASA archives are active participants in this process and in particular the ADS is leading the NASA effort to incorporate Digital Object Identifiers (DOIs) in referencing both data and publications.

This paper discusses our model, the progress we have made in implementing it, and the challenges that we – and likely other archives – will face in providing compatible interfaces to astronomical data using the virtual observatory standards.

9910-11, Session 4

Public surveys at ESO

Magda Arnaboldi, Nausicaa A. R. Delmotte, Michael Hilker, Gaitee Hussain, European Southern Observatory (Germany); Laura Mascetti, Terma GmbH (Germany); Alberto Micol, Monika Petr-Gotzens, Marina Rejkuba, Joerg Retzlaff, European Southern Observatory (Germany); Steffen Mieske, Thomas Szeifert, European Southern Observatory (Chile); Martino Romaniello, Bruno Leibundgut, Rob J. Ivison, European Southern Observatory (Germany)

This paper presents an overview of the fourteen ESO public survey projects completed or on going at the ESO facilities (Survey telescopes, VISTA and VST, on the VLT instruments, UVES, FLAMES, VIMOS, and MUSE, and on the NTT, with SOFI and EFOSC) at the La Silla-Paranal Observatory. The paper outlines the motivations behind these large projects, the policies, tools and services in place to support and monitor the execution of these programmes at the telescopes, and their current completion status. The paper presents how these programmes continue to publish their data through the ESO Science Archive Facility, and from then on how they become accessible to the astronomical community. It concludes with an outlook on the future developments of public surveys at ESO, with the recent call for VISTA public surveys and the wide area spectrographs 4MOST and MOONS.

9910-12, Session 4

Not letting the perfect be the enemy of the good: steps toward science-ready ALMA images

Amanda Kepley, Jennifer Donovan Meyer, Crystal Brogan, Arielle Moullet, John E. Hibbard, Remy Indebetouw, Brian S. Mason, National Radio Astronomy Observatory (United States)

Historically, radio observatories have placed the onus of calibrating and imaging data on the observer, thus restricting their user base to those already initiated into the mysteries of radio data or those willing to develop these skills. To expand its user base, the Atacama Large Millimeter/submillimeter Array (ALMA) has a high-level directive to produce calibrated visibilities and images from these visibilities for PIs. Although an ALMA calibration pipeline is in place, all images continue to be produced for the PI by hand. In this talk, I will describe on-going efforts at the Northern American ALMA Science Center to produce more uniform imaging products that more closely meet the PI science goals and provide better archival value. As a first step, the NAASC imaging group produced a simple imaging template designed to help scientific staff produce uniform imaging products. This script allowed the NAASC to maximize the productivity of data analysts with relatively little guidance by the scientific staff by providing a step-by-step guide to best practices for ALMA image. Finally, I will describe the role of the manually produced images in verifying the imaging pipeline and the on-going develop of said pipeline. The development of the imaging template, while technically simple, shows how small steps toward unifying processes and sharing knowledge can lead to large gains for science data products.

9910-13, Session 4

Science data management at ESO

Martino Romaniello, European Southern Observatory (Germany)

Providing the best science data is at the core of ESO's mission to enable major science discoveries from our science community. I will briefly describe the steps that ESO undertakes to fulfill this, namely ensuring that instruments are working properly, that the science content can be extracted from the data and, finally, delivering the science data to our users, PIs and archive researchers alike.

Metrics and statistics that gauge the results and impact of these efforts will be discussed.

9910-14, Session 5

ANTARES: a time-domain broker for the LSST era

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The Arizona-NOAO Temporal Analysis and Response to Events System (ANTARES) is a joint project of the National Optical Astronomy Observatory and the Department of Computer Science at the University of Arizona. The goal is to build the software infrastructure necessary to process and filter alerts produced by time-domain surveys, with the ultimate source of such alerts being the Large Synoptic Survey Telescope (LSST). The ANTARES broker adds value to alerts by annotating them with information from external sources such as previous surveys from across the electromagnetic spectrum. In addition, the temporal history of annotated alerts will provide further elucidation for analysis. Also incorporated is a "touchstone," a knowledge repository of properties and features of known or predicted kinds of variable astronomical sources. An incoming alert's features can be compared to the information in the touchstone through a series of filtering stages to ascertain whether it is 'interesting.' For the prototype, 'interesting' is defined as the rarest or most unusual alert, or alerts that need immediate follow-up observations, but the architecture supports incorporating alternate logic and goals. The system is designed to be flexible, allowing users to access the stream at multiple points throughout the process and to insert custom filters where necessary. The repository of annotated alerts, including association with known objects in the sky is an additional data product that can serve the needs of users seeking categories of time varying phenomena that are not critical for immediate follow up. In addition to its projected scientific scope, we describe the current state of development of ANTARES, examples of some working algorithms, its architecture and scalability, operational stability, and development time-line.

9910-16, Session 5

DDOTI: the deca-degree optical transient imager

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Ruiz, Observatorio Astronómico Nacional (Mexico); Carlos G. Román-Zúñiga, Univ. Nacional Autónoma de México (Mexico); Pierre Thierry, Observatoire de Roudiere (France); Eleonora Troja, NASA Goddard Space Flight Ctr. (United States)

DDOTI will be a wide-field robotic imager consisting of six 28-cm telescopes with prime focus CCDs mounted on a common equatorial mount. Each telescope will have a field of view of 12 square degrees with 2 arcsec pixels, and the set of six will provide an instantaneous field of view of about 72 square degrees. DDOTI uses commercial components almost entirely. The five-sigma limiting magnitude will be about magnitude 19 in 60 seconds. DDOTI will be installed at the Observatorio Astronómico Nacional in Sierra San Pedro Martír, Baja California, México in late 2016.

The main science goal of DDOTI is the localization of the optical transients associated with GRBs detected by the GBM instrument on the Fermi satellite. DDOTI can cover the majority of the typical initial error region of 100 square degrees in just two pointings. We expect that DDOTI will be able to quickly localize about 45 GBM GRBs per year, about 20% of the total detected by GBM. Fast localizations will permit spectroscopy from larger telescopes to determine the redshift, which is currently unknown for the vast majority of GBM GRBs. Thus, DDOTI promises to be a key part of a chain that will allow us to fully exploit the GBM instrument. DDOTI will also be used to follow-up gravity-wave transients, for studies of AGN and YSO variability, and to determine the occurrence of hot Jupiters.

The principal advantage of DDOTI compared to other similar projects such as iPTF, ZPTF, and BlackGEM is cost: a single DDOTI installation costs only about US$500,000. This makes it possible to contemplate a network of DDOTI installations around the world. Such geographic diversity would give faster access to GBM GRBs and a higher localization and follow-up rate.

In this contribution, we will discuss the DDOTI hardware and software, our tests on the sky of the single-telescope prototype, our reference science cases, the state of the six-telescope imager for the Observatorio Astronómico Nacional, and our plans for a future world-wide network.

9910-98, Session 5

CARMENES: data flow

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The long CARMENES acronym, Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs, consists actually of a few words that are carefully chosen. This new instrument, built by a consortium of German and Spanish institutions, is as complex as expected for a spectrograph that covers for the first time from 0.55 to 1.70 mum in only one shot and that has enough high resolution and thermo-mechanical stability for reaching the 1 m/s accuracy. CARMENES consists of a number of subsystems: (i) a front-end in the Cassegrain focus of the 3.5 m Calar Alto telescope with a pick-up mirror, and double-prism atmospheric dispersion corrector, an acquisition and guiding system, a dichroic at 0.95 mum, and a double fibre input unit; (ii) an optical-fibre relay system (including both circular and octagonal fibres) with a fibre shaker; (iii) two spectrographs, one for the visible region bluewards of 0.95 mum, the other one for the near-infrared region redwards of it, each of them with no movable parts but with a continuous cooling-flow detector cryostat, a reliable vacuum system with pumps and liquid N2 pipes, an exposure-meter, and numerous pressure, temperature and valve sensors; (iv) a cooling unit for the near-infrared channel based on a continuous flow of gaseous N2; (v) two calibration units, one for each channel, with hollow cathode lamps and flat-field halogen lamps, shutters and filters; (vi) two Fabry-Pérot etalons for simultaneous wavelength calibration; (vii) three air-conditioned rooms for the near-infrared spectrograph, the visible spectrograph and the calibration devices; (viii) a double interlocks system for safety control of hazardous items; (ix) an instrument control with a friendly graphical user interface and an automatic scheduler; and (x) an automatic pipeline that provides the observer with extracted spectra and computed radial velocities less than one minute after the end of the exposure. A dozen main computers, not counting spares, control the whole system. Together with the acquisition-and-guiding images, visible and near-infrared spectra, exposure meters data (number of counts per second during exposure as measured in the zeroth order of the échelle grating) and pipeline output files, we store over 250 parameters per observing block in the corresponding fits headers (from local sidereal time, through V-band seeing, age of used hollow cathode lamp and current of the fibre shaker, to temperatures in 16 locations on the near-infrared optical bench). In the following morning, all data are copied to a computer in the Calar Alto observatory, from which they are retrieved, stored and made available to the consortium members or to the public through a virtual-observatory data server located in Madrid. Eventually, all the CARMENES data, raw and/or processed, arrive on the same day to the astronomers' computers in a friendly, comprehensive and automatic way.

9910-17, Session 6

Operations concept for the Square Kilometre Array

Gary R. Davis, SKA Organisation (United Kingdom); Douglas C. Bock, CSIRO Astronomy and Space Science (Australia); Antonio C. Chrysostomou, Cornelius Taljaard, SKA Organisation (United Kingdom)

The Square Kilometre Array (SKA) is an ambitious project to build the world's largest radio telescope, eventually reaching one square kilometre in collecting area. When complete it will be one of the world's engineering marvels. The first phase of the project, SKA1, will consist of two telescopes: SKA1-LOW, comprising ~131,000 dipole antennas at the Murchison Radio Observatory in Western Australia covering the range 50–350 MHz, and SKA1-MID, comprising ~200 x 15-m dishes in the Karoo desert in South Africa covering the range 0.35–13.8 GHz. SKA1 is scheduled to commence operations in 2023 and, in order to appropriately influence the design of the system, operational planning has commenced. This paper will report on the initial stages of developing the operational concept and its implementation.

The science programme for the SKA is not yet defined, but is expected to consist of both large projects requiring more than 1000 hours of observing time (Key Science Projects), and conventional, smaller, PI-driven programmes. The observatory is required to support both types of project, and also to deliver appropriate return on investment for the partner countries. The science programme is significantly integrated between the two telescopes and operations will therefore emphasise the commonalities between LOW and MID as far as practicable.

The concept for science operations has been developed with the goal of delivering maximum scientific impact within the available resources. Observations will be carried out in service mode for 24hr/day, using flexible queue scheduling, all to enhance observational efficiency. Targets

of Opportunity and transients form an important part of the SKA's science case, and the observing system will automate these observations to the maximum possible extent. The flexibility of the system will enable multiplexing of observations in various ways: e.g., configuration of the two telescopes into multiple, independent sub-arrays for simultaneous observations, or sharing of datasets between multiple science teams. In collaboration with the SKA member states, a high level of user support will be provided to ensure that the diverse, world-wide user community is able to fully exploit the observatory's capabilities.

The concept for engineering operations is based on the requirement for high availability. The system is being designed for high reliability, and maintenance in the field will be strictly limited, based on replacement of modular units.

The SKA will generate unprecedented volumes of data, leading to the requirements for high-performance computational capabilities at the back end of each telescope for the generation of data products and for innovative arrangements for further science processing and distribution to end users. The data flow concept is currently under study and will likely be based on a global network of coordinated, regional science and data centres.

Implementation of this operational concept requires the development of an organisational structure that reflects the unique nature of the SKA as a globally-distributed observatory, with telescopes in two countries and a headquarters in a third (the UK), and with data centres and technology development centres throughout the member countries.

9910-18, Session 6

A preliminary operations concept for the ngVLA

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A future large area radio array optimized to perform imaging of thermal emission down to milliarcsecond scales is currently under consideration in North America. This `Next Generation Very Large Array' (ngVLA) will have ten times the effective collecting area of the JVLA, operate from 1GHz to 115GHz, have ten times longer baselines (300 km), and include a dense core on kilometer scales for high surface brightness imaging. The current VLA site in the southwest USA is being considered as a possible location for the ngVLA.

The large number of antennas and their large geographical distribution pose significant challenges to ngVLA operations and maintenance which must be addressed in the early stages of the project to minimize operations cost while maximizing the scientific productivity of the instrument. We draw on experience from operating the JVLA, VLBA, and ALMA to highlight notable operational issues and outline a preliminary operations concept for the ngVLA.

For array operations and maintenance, a number of features are planned to reduce the operational costs of the ngVLA. Current plans call for the antennas to be fixed in location. Maintenance at each antenna will be minimized by building high reliability into antenna systems and components, modularizing components to facilitate quick repairs, and providing remote resets or reboots of systems to minimize antenna maintenance visits. While maintenance operations will be concentrated at the array core, a set of small satellite maintenance teams will service the antennas on longer baselines on a continuous basis. Antenna sites should be readily accessible via existing roads to minimize observatory maintenance of the roads it must build for antenna access. Electrical power will be taken from local grids, with the goal of tapping into those with renewable energy (solar and wind) as their power generation source. In an effort to minimize antenna power consumption, a development program has been initiated to improve the efficiency of cryogenic cooling systems through the use of variable speed drives.

For science operations, the ngVLA is envisioned to be a general purpose, PI-driven, pointed telescope, much like the JVLA, as opposed to a survey instrument that delivers generic data products. The array will be fully dynamically scheduled to match weather, phase stability, and other criteria to observer requirements in order to improve observing efficiency. Dynamic scheduling will also enable time critical observations within a few hours of triggering. A flexible data reduction system will be provided; pipeline operations will be implemented for calibrating data and generating image products, but multi-access to raw data, calibrated data, and image products will also be provided to users ranging from novice to expert to ensure that data delivery to investigators is not unnecessarily delayed. Given the number of antennas and receiver bandwidths, data rates from the ngVLA will be large, suggesting that data processing will be done in remote batches, either on dedicated localized hardware or on cloud resources.

9910-21, Session 6

A new procedure to maintain and calibrate very large geographically distributed radio telescope arrays

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In the recent years the design of radio-telescopes has been oriented towards very large geographically distributed array systems, such as SKA system.

For the proper operation of the system the antennas are to be kept in phase so that they behave as a single very large antenna. This result is obtained through a very accurate timing ,analogue to digital (AD) conversion of the signals received by the individual antennas, and a very sophisticated life cycle design, capable of maintaining the performance of the large array along a very large time window of years (at least 20).

In order to maintain the system efficiency, it is therefore advisable to routinely perform a check of the electromagnetic performance of each antenna and of each antenna with respect to the others. This periodic monitoring and correction system, should be obtained avoiding conventional calibration procedures, which are a very expensive and time consuming task.

The procedure proposed in this paper considers two major sources of errors:

• The former due to changes with respect to modification of the antenna (or the feed) geometry.

• The latter due to variations of the antenna location one with respect to the others.

On the Antenna Geometry verification it has to be noted that acceptance tests include a dimensional check of the optics as well as an electromagnetic test (radiation solid). The radiation solid allows to diagnostic the optics impairments if any inclusive of the ones due to the geometrical impairments. The time required to perform these tests ranges from days to weeks. This is acceptable for a single antenna whereas it is not for hundreds of antennas to be monitored routinely. The alternative method proposed in the paper to perform test on the far field radiation pattern using the Airy zone of the focal plane ("Airy disk"). The measurement allows to get the antenna behavior with a single synoptic test.

On the location of each antenna with respect to each other, i.e. with respect to a common reference system the paper proposes the combined use of GNSS satellite (using the RTK function) and radio images obtained from SAR satellite interferometry.

The proposed methodology allows the control of the mutual positions of the elements of the array in real time, simplifying the procedure of

managing the life cycle of such an infrastructure.

For the deployment time of future radio telescope arrays the Galileo Constellation in addition to GPS will be available, while SAR satellite are already available now. The combined use of these solutions supplies a powerful tool for analysis and operational monitoring implementing a very accurate “three-dimensional matrix” presenting the positioning errors of geographically distributed arrays and supporting the maintenance and calibration procedures along the years.

9910-23, Session 6

Centralized operations and maintenance planning at the Atacama Large Millimeter/submillimeter Array (ALMA)

Bernhard Lopez, Nicholas D. Whyborn, Serge Guniat, Octavio Hernandez, ALMA (Chile); Stefan Gairing, Joint ALMA Observatory (Chile)

The Atacama Large Millimeter/submillimeter Array (ALMA) is a joint project between astronomical organizations in Europe, North America, and East Asia, in collaboration with the Republic of Chile. ALMA consists of 54 twelve-meter antennas and 12 seven-meter antennas operating as an aperture synthesis array in the (sub)millimeter wavelength range.

Since the inauguration of the observatory back in March 2013 there has been a continuous effort to establish solid operations processes for effective and efficient management of technical and administrative tasks on site. Here a key aspect had been the centralized maintenance and operations planning: input is collected from science stakeholders, the computerized maintenance management system (CMMS) and from the technical teams spread around the world, then this information is analyzed and consolidated based on the established maintenance strategy, the observatory long-term plan and the short-term priorities definitions.

This paper presents the high-level process that had been laid out for the planning and scheduling of planned- and unplanned maintenance tasks, and for site operations like the telescope array reconfiguration campaigns. We focus on the centralized planning approach by presenting its genesis, its current implementation for the observatory operations including related planning products, and we explore the necessary next steps in order to fully achieve a comprehensive centralized planning approach for ALMA in steady-state operations.

9910-25, Session 6

Power monitoring and control for large scale projects: SKA: a case study

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Large sensor-based science infrastructures for radio astronomy like the SKA will be among the most intensive data-driven projects in the world, facing very high demanding computation, storage, management, and above all power demands. The geographically wide distribution of the SKA and and its associated processing requirements in the form of tailored High Performance Computing (HPC) facilities, require a Greener approach towards the Information and Communications Technologies (ICT) adopted for the data processing to enable operational compliance to strict power budgets. Addressing both the reduction of electricity costs and the generation and management of electricity at system level is paramount to avoid future inefficiencies and higher costs, while enabling fulfillments of Science Cases like Transient observations or other Virtual Observatory (VO) triggered observations whose operational modes may produce sudden peak power loads. In particular, since the (power hungry) data processing location is conditioned by the experiment, and not by the computational facilities, it results in far from optimal efficiency, higher capital expenditure (CAPEX) and higher OPEX. As an example, VO triggered events will require precise metering, operating under the constraints of Power forecast budget, while considering power buffer allocations for these unexpected, yet extremely relevant astronomical events. Management of these operational modes require power forecast at subsystem level and power buffers, eventually with reconfiguration, disconnection or graceful operational downgrade of some other telescope components. Hence, at system planning, we must consider a combination of low power computing, efficient data storage, local data services, Smart Grid power management, and potential inclusion of other non-grid sources like Renewable Energies in the form of heterogeneous system mix, and a heterogeneous power mix at provision level.

Of particular importance, Smart Grid technologies enable power management and control (M&C) at component level through a combination of distributed IT, field automation, remote sensors and its wealth of endpoints. These attributes will drive the functional integration of new distribution management capabilities into the SKA telescope’s instances though its energy management centers. Besides greater efficiency, the Smart Grid technologies benefits include detailed power forecasts, improved service reliability, more efficient power asset management, and better operational planning. Power monitoring of systems antennas and ancillary systems, Correlators, HPC facilities or related data center tiered systems must include advanced metering technologies, efficient distribution automation and Network Operation Centers (NOC).

Here we outline the major characteristics and innovation approaches to address power efficiency, lifecycle impact and long-term power sustainability for radio astronomy projects like the SKA.

9910-28, Session 6

The Australian SKA Pathfinder: operations management and user engagement

Lisa Harvey-Smith, CSIRO Astronomy and Space Science (Australia)

The Australian SKA Pathfinder is an innovative new radio telescope comprising 36 parabolic dishes fitted with ‘phased array feeds’ - radio cameras with a 30 square degree instantaneous field-of-view. For the first five years of ASKAP operation, approximately 75% of the available observing time will be dedicated to large surveys, with the remainder being available for guest science projects.

ASKAP is currently in its final stages of construction and is being commissioned by a team of astronomers and engineers. The ASKAP early science program will begin in 2016, in parallel with continued receiver integration and commissioning. The major ASKAP surveys will begin in 2018.

In this talk, the ASKAP Project Scientist will describe how the observatory has engaged the major ASKAP survey teams throughout the telescope design process, how plans have changed in light of a major re-design of the receiver systems, what preparations are being made for survey-mode observatory operations (including operator interfaces, survey optimisation tools, operations benchmarks and metrics) and describe lessons learned.

9910-125, Session 6

STELLA: 10 years of robotic observations Tenerife

Michael Weber, Thomas Granzer, Klaus G. Strassmeier, Leibniz-Institut für Astrophysik Potsdam (Germany)

STELLA is a robotic observatory on Tenerife, which is currently housing two 1.2m robotic telescopes. One telescope is fibre-feeding a high-resolution (R=55,000) echelle spectrograph (SES), while the other telescope is equipped with a visible wide-field (FOV=22'x22') imaging instrument (WiFSIP). Robotic observations started mid 2006, and the primary scientific driver is monitoring of stellar-activity related phenomena.

The STELLA control system (SCS) software package was originally tailored to the STELLA roll-off style building and high-resolution spectroscopy, but was extended over the years to support the wide-field imager, an off-axis guider for the imager, separate acquisition telescopes, classical domes, and targets-of-opportunity. The SCS allows for unattended, off-line operation of the observatory, targets can be uploaded at any time and are selected based on merit-functions in real-time (dispatch scheduling).

We report on the current status of the observatory and the current capabilities of the STELLA control system.

9910-20, Session 7

LBTO's long march to full operation: step 2

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The march of the Large Binocular Telescope Observatory to full operation is a long journey, which is both exciting and challenging. Exciting as the long awaited suite of first generation instruments and GLAO will eventually become available for binocular operations, while regular interferometric observations will make LBT the first operational ELT. Challenging because LBTO will have to handle maintenance and upgrades of instruments or key components like its adaptive secondaries about which it has much to learn.

Step1 outlined a a six-year plan aimed at optimizing LBTO's scientific production while mitigating the consequences of the inevitable brought on by the considerable complexity of the telescope and the very diverse nature of the LBTO partnership.

Step 2 will focus on the first two years of implementation of this plan, presenting the encountered obstacles, technical, cultural, and political, and how they were overcome. It will also highlight milestones such as the completion of the commissioning of the first generation instruments now available for binocular operations and the first science publications using LBT as a 23-m telescope through interferometry.

9910-22, Session 7

Response to major earthquakes affecting Gemini twins

Michiel van der Hoeven, Rolando Rogers, Gemini Observatory (Chile); Mathew J. Rippa, Gemini Observatory (United States); Gabriel Perez, Vanessa Montes, Cristian Moreno, Gemini Observatory (Chile)

Both Gemini telescopes, in Hawaii and Chile, are located in highly seismic active areas. That means that the seismic protection is included in the structural design of the telescope, instruments and auxiliary structure. We will start this paper by introducing the specific design features to reduce permanent damage in case of major earthquakes. At this moment both telescopes have been affected by big earthquakes in 2006 and 2015 respectively. There is an opportunity to compare the original design to the effects that are caused by these earthquakes and analyze their effectiveness.

The paper describes the way the telescopes responded to these events, the damage that was caused, how we recovered from it, the modifications we have done to avoid some of this damage in future occasions, and lessons learned to face this type of events. Finally we will cover on how we pretend to upgrade the limited monitoring tools we currently have in place to measure the impact of earthquakes.

9910-24, Session 7

Technical maintenance activities at Paranal Observatory

Maxime Boccas, Eva Díaz Catalá, Michel Frantz, Javier Gonzalez, Sergio E. Gonzalez, Gerhard Hüdepohl, Ismo Kastinen, Alex Morales, Matteo Pozzobon, Christian Ramirez, Claudio Reinero, Fernando Salgado, Waldo Siclari, Christian Stephan, Javier Valenzuela, European Southern Observatory (Chile)

After more than 15 years of operation, the Paranal Observatory has accumulated a lot of experience with maintenance of systems, and has recently adopted the methodology called Maintien en Condition Operationnelle (MCO). We will describe and review the practical implementation of this strategy, the tools used, the benefits and challenges as well as practical examples and how it is overall managed. The approach is also a benchmarking exercise for operation of the E-ELT in the future.

9910-26, Session 7

Worth its SALT: four years of full science operations with the Southern African Large Telescope

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SALT is a 10-m class optical telescope located in Sutherland, South Africa, owned by an international consortium and operated in fully queue-scheduled mode by the South African Astronomical Observatory.

In this paper we present an update on all observatory performance metrics since the start of full science operations in late 2011, including science time, weather and technical downtime, and time used for planned engineering activities and commissioning. We analyze key statistics describing the science output of SALT, the completion fractions of scheduled observations and programs per priority class, and analyze the more than 120 refereed papers to date since first light based on SALT data.

There has been a steady improvement in statistics under our control over the four years. In particular, the efficiency at which the time available

for science is converted to completed observations and programs has increased significantly, while the downtime due to technical or operational problems has decreased steadily. In the second semester of 2015, SALT completed 80% of the highest science priority observations in the queue. Full program completeness is lower, however, due to many programs splitting their time over high and low priorities, and we discuss the possible effects of this policy. We also discuss the many layers of software developed to maintain the efficiency in planning programs, streamlining the scheduling and tracking of their execution, and reducing the data. Some of these, along with the latest developments in instrumentation and engineering projects, are presented in detail in other SPIE paper submissions.

The refereed paper output has been increasing, with 35 papers during the 2015 calendar year. When counted from the start of science operations, we show that the trend is very similar to other 6-10 m observatories when scaled by the number of telescopes. In particular, when scaled by operations costs, where known, we show that SALT is very cost-effective compared to most other large telescope operations. We discuss the lessons learned in striving to make the most of SALT within the constraints of its design and site characteristics, including the challenging goal of guiding the user community to maximize outputs by utilizing the strengths of the telescope.

By far the most papers on SALT are based on data from the Robert Stobie Spectrograph (RSS) and, not surprisingly, the most efficient output to date is with long-slit spectroscopic observations. Modes requiring more specialist knowledge in reductions, multi-object spectroscopy and Fabry-Perot imaging spectroscopy, are more rare but are also starting to produce refereed publications. The hand-over to SALT Operations of the newest instrument, the High Resolution Spectrograph (HRS, status of which is described in another SPIE submission), happened in 2015, and the instrument has just seen its first data published. We discuss the need for a data reduction pipeline in making the science output of this type of instrument efficient.

Finally, we also present the operational structure of the SALT organization, in particular since moving to an integrated operations team in 2015.

9910-27, Session 7

A collimated beam projector for precise LSST throughput calibration

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The precise determination of the instrumental response function vs. wavelength is a central ingredient in contemporary photometric calibration strategies. This typically entails sending narrowband illumination through the system pupil, and comparing the detected photon rate across the focal plane to the amount of incident light as measured by a calibrated photodiode. But stray light effects and reflections/ghosting (especially on the skirts of filter passbands) in the optical train constitute a major source of systematic uncertainty when using a flat-field screen as the illumination source. A collimated beam projector (CBP) that illuminates a mask onto the focal plane of the instrument can distinguish focusing light paths from stray and scattered light, allowing for a precise determination of instrumental throughput. We describe the conceptual design of such a system, outline its merits, and present results from a prototype system used with the DECam wide field imager on the 4 meter Blanco telescope. We also present a calibration scheme that blends results from flat-field images with CBP data, to obtain the equivalent of an illumination correction, at high spectral and angular resolution. In addition to providing a precise system throughput calibration, by monitoring the evolution of the intensity of the ghosts in the optical system, the CBP can be used to track the evolution of the filter transmission properties and various anti-reflection coatings in the optical system.

The basic design concept is as follows. An optical fiber (monochromatic or any other desired spectral distribution) brings light originating from some source to an integrating sphere. The light then travels through a shutter to a filter wheel containing a set of ten filters which allows a choice of a variety of mask patterns. After the light has been modified it travels through the focuser, translation stage, collimating telescope, and out of the system. The light is then re-imaged onto the telescope focal plane. The collimator optic will reside inside of the enclosure on an alt-az type mount so that the collimated beam can be re-imaged onto any desired location on the focal plane. With the additional freedom of moving the telescope within the enclosure, the collimated beam can achieve any desired position within the telescope's input pupil. Consequently, the entire 4-d phase space of input ray positions and angles, in principle, can be scanned.

9910-29, Session 7

The JCMT as operated by the East Asian Observatory: a brief (but thrilling) history

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The newly formed East Asian Observatory assumed operations of the James Clerk Maxwell Telescope in March of 2015. In just three weeks, the facility needed to run up completely mothballed observatory operations, introduce the telescope to a vast new scientist base with no familiarity with the facility, and create a non-existent science program. The handover to the EAO has since been a succession of challenging time-lines, and nearly unique problems requiring novel solutions. The results, however, have been spectacular, with subscription rates at unprecedented levels, a new series of Large Programs underway, as well as an exciting Future Instrumentation Project that together promises to keep JCMT at the forefront of wide-field submillimeter astronomy for the next decade.

9910-30, Session 7

SOAR Telescope operation in the LSST era: real-time follow-up on large scales

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The SOAR telescope will be well situated, both in terms of location and aperture, to follow up on the stream of brighter transient events generated by the Large Synoptic Survey Telescope (LSST). A critical aspect is that the operation is less likely to be responding to occasional targets of opportunity, and more likely to be responding to a continuing follow of events that must be efficiently prioritized and observed. We discuss the implications for observatory operations, including potential modifications to the telescope itself or to the instrument suite. Representative "use cases" are described to assist in putting potential operational modes into context.

9910-31, Session 7

Organizational transformation to improve operational efficiency at Gemini South

Michiel van der Hoeven, Diego Maltes, Rolando Rogers, Gemini Observatory (Chile)

In this paper we will describe how the Gemini South Engineering team has been reorganized from different functional units into a cross-disciplinary team while executing the transition plan that imposes several staff reductions. While this implies we have a more self-contained engineering team at each site to cover routine operations, we still aim to maintain some sharing of expertise on specialist activities between both sites in Chile and Hawaii.

This reorganization process has been triggered by the budget cuts as a result of the withdrawal of one of the major partners in the Gemini consortium. Whereas these reductions in budget pose severe limitations on how the observatory can operate, at the same time it has provided an opportunity to streamline all the processes.

We will compare how problems are approached under the system based organization and discuss the benefits and challenges we have come across. During any change in organization, the alignment of several factors in such organization is of critical importance in order to be successful. Budgetary processes, staff diversity, leadership style, skill sets and planning are all important factors to take into account to achieve a successful outcome. We will analyze the organizational alignment by using some proven management models and concepts.

Gemini South is placed in a very dynamic and exciting environment with many new astronomy projects coming on-line, now and over the coming years. It becomes a real challenge to maintain a competent and experienced workforce with many new opportunities coming up. By joining forces between the AURA centers (of which Gemini forms part) we have are actively working on sharing resources, that provides interesting career perspectives and leads to staff retention and as well making the overall operation of AURA telescopes more efficient.

Finally we will give some examples how at Gemini we have been searching for creative solutions to do the same with less by activating our (local) community and outsourcing some activities.

9910-32, Session 7

CARMENES-NIR channel spectrograph: how to achieve the full AIV at system level of a cryo-instrument in nine months

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CARMENES is the new high-resolution high-stability spectrograph built for the 3.5m telescope at the Calar Alto Observatory (CAHA, Almería, Spain) by a consortium formed by German and Spanish institutions. This instrument is composed by two separated spectrographs: VIS channel (550-1050 nm) and NIR channel (900-1700 nm). The NIR-channel spectrograph's responsible is the Instituto de Astrofísica de Andalucía, IAA-CSIC. The channel has been manufactured, assembled, integrated and verified in the last two years. It was delivered to the observatory in fall 2015, and commissioned in December 2015. The expected performances comply with the scientific requirements and its science verification started.

The contouring conditions of this project have led the CARMENES instrument to be a schedule-driven project with a very tight planning. This plays in contradiction to the very complex, calm-requiring tasks and development phases faced during the Assembly, Integration and Verification (AIV) of the NIR-channel spectrograph. In particular, the AIV at system level has been fully designed and implemented at IAA through a very ambitious and zero-contingency plan. This NIR-channel AIV plan has been continuously reviewed and agreed along the project with the CARMENES overall, high-level plan –coordinating the needs of both channels as a whole- developed by the FRACTAL company, holding the Systems Engineering and Project Management of the instrument.

As a large cryogenic instrument, the NIR channel's AIV plan at system level includes necessarily a certain number cryo-vacuum cycles, this factor being the most important for the overall duration of this phase. Indeed, each cryo-vacuum cycle of the NIR-channel runs during 3 weeks roughly to lead the instrument from atmospheric conditions to cryo-vacuum working conditions and again to atmospheric conditions in warm. This plan has therefore been driven to minimize the amount of cryo-vacuum cycles.

Such huge effort has led the AIV at system level at IAA lab to be executed in 9 months from start to end -an astonishingly short duration for a large cryogenic, complex instrument like CARMENES NIR channel- which has been fully compliant with the final deadline of the installation of the NIR channel at CAHA 3.5m telescope. The detailed description of this planning, as well as the way how it was actually performed, is the main aim of the present paper.

9910-33, Session 7

Precipitable water vapour statistical results at Teide Observatory from a routine GPS monitor

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We present statistical results of Precipitable Water Vapour (PWV) at Teide Observatory (OT) since 2009 from a new PWV GPS monitor that has been commissioned at the OT for routine operation in real time. The software for the data processing was validated with other different monitor using the same GPS antenna. On the other hand, the GPS technique itself, was validated by inter-comparison with the output of the Weather Research and Forecasting (WRF) numerical model, previously calibrated with in-situ radiosounding data.

9910-72, Session PWed

ASTRI SST-2M archive system: a prototype for the Cherenkov Telescope Array

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The ASTRI SST-2M is a dual-mirror, small-sized, end-to-end Cherenkov telescope prototype developed by the Italian National Institute for Astrophysics (INAF) in the framework of the Cherenkov Telescope Array (CTA) gamma-ray observatory. Data preservation and accessibility is guaranteed by means of the ASTRI SST-2M Archive System (AAS) that is responsible for both the on-site and off-site archiving of all data produced by the different ASTRI SST-2M prototype sub-systems. Science, calibration, and Monte Carlo data together with the dedicated Instrument Response Functions (IRFs) (and corresponding metadata) will be properly stored and organized in different branches of the archive. A dedicated technical data archive (TECH archive) will store the engineering and auxiliary data and will be organized under a parallel database system. Through the use of a physical system archive and few logical user archives that reflect the different archive use-cases, the AAS has been designed to be independent from any specific data model and storage technology. A dedicated framework to access, browse and download the telescope data has been identified within the proposal handling utility that stores and arranges the information of the observational proposals. The development of the whole archive system follows the requirements of the CTA data archive and is currently carried out by the INAF-OAR & ASI-Science Data Center (ASDC) team. The prototype AAS is fully adaptable and ready for the ASTRI mini-

array that, formed of nine ASTRI SST-2M telescopes, is proposed to be installed at the CTA southern site.

9910-73, Session PWed

The usefulness and dangers of relying on grant acknowledgments in an observatory bibliography

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The Chandra Data Archive has been maintaining an observatory bibliography for many years by: 1) searching for broad key words, such as "x-ray", in the ADS to find all potential ADS records which may contain Chandra references; 2) accessing those articles in an automated way to perform a full-text search of the article for specific words such as "Chandra"; and 3) reviewing those articles which have passed the first two tests to assess their inclusion in the bibliography. During the assessment phase, we link Chandra data used in the article to the article's bibcode and use this linking as the starting point for measuring the scientific impact of the Chandra observatory. We also make determinations based on data links, author lists, and principal investigators (PI) to assess the impact of PI teams.

In addition to observing programs which result in new Chandra data, the Chandra X-ray Center also provides funding for archival research or theoretical work using public Chandra data. Assessing the science impact of these programs is difficult to assess from a bibliography based on data links. However, recently the Chandra Data Archive (CDA) has obtained access to funding information related to all approved Chandra proposals and we intend to use grant information acknowledged in manuscripts to assess these programs. Using grant acknowledgments is becoming a popular means of maintaining observatory bibliographies, but the accuracy of this method is difficult to assess. The CDA is in a unique position to compare program statistics based on grant acknowledgments to those based on data links. The purpose of this paper is to present in a quantitative way an assessment of how well grant and/or program acknowledgments reflect the scientific impact of Chandra observing, archive and theory programs.

This work is supported by NASA contract NAS8-03060.

9910-74, Session PWed

Gemini base facility operations environmental monitoring: key systems and tools for the remote operator

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In 2013 Gemini Observatory started the base facility operations (BFO) project. The project's goal is to provide the ability to operate the two Gemini telescopes from their base facilities (respectively Hilo, HI at Gemini North, and La Serena, Chile at Gemini South). BFO has been identified as a key project for Gemini's transition program as it creates an opportunity to reduce operation costs. The Gemini North telescope started remote operations from the Hilo base facility in Hawaii in November 2015, and we are starting the process at Gemini South to implement BFO by 2016.

In order to provide night-time staff with the necessary tools for remote observing, the following critical environmental factors that affect night time observations were identified: wind speed, outside temperature, outside humidity, outside dew point, precipitation, ice on the dome, precipitation, cloud cover, presence of fog and earthquake detection. This paper focuses on the environmental monitoring portion of the BFO project, which is needed to inspect these critical factors. For the Gemini North telescope we divided environmental monitoring into the following work packages: weather sensor upgrades (wind speed, temperature, humidity, precipitation, and ice), cloud-sensing systems (cloud cover), fog detection (A&V) and earthquake detection system (earthquake detection). All these work packages have been successfully implemented at Gemini North by the author and co-authors of this paper. For Gemini south telescope these four work packages have been consolidated into one larger work package for environmental monitoring.

This paper will show the methods and design used at the Gemini North and Gemini South telescopes to monitor these critical environmental conditions.

9910-75, Session PWed

Approximations of the synoptic spectra of atmospheric turbulence by sums of spectra of coherent structures

Vladimir P. Lukin, Viktor V. Nosov, Andrey V. Torgaev, Evgeny V. Nosov, V.E. Zuev Institute of Atmospheric Optics (Russian Federation)

In article it is shown that at measuring of turbulent parameters it is enough, that the interval of the registered frequencies of fluctuations overlapped the most part of a micro-meteorological interval of a spectrum of atmospheric turbulence as interval the basic energy of turbulent fluctuations of a surface layer is concentrated. At measuring of the meteorological parameters related to low-frequency daily and seasonal changes of a meteo-situation, often it is already not enough width of one this interval. In this case averaging time at the parameter recording is usually incremented from 2-3 minutes to 10 minutes (and more), at the expense of expansion of an interval of measured frequencies.

In the range of continuances from minutes till several hours the field of a mezzo-meteorological minimum is observed in a spectrum of atmospheric turbulence. Spectra again start to increasing in low-frequency field (at decrease of frequency), transiting through the intermediate 12 hour maximum, and reach a synoptic maximum (a continuance of fluctuations about 4-6 days), and then again decrease. Synoptic spectrums viewed in given article cover a wide frequency band, including the micrometeorological, mezo-meteorological and synoptic intervals. On the basis of theoretical Karman model of a three-dimensional spectrum of the temperature fluctuations the theoretical spatial one-dimensional spectrum of a single coherent structure has been found. Use of such spectrum has allowed us to show that the experimental spectrums of a really observable atmospheric turbulence (with frequencies from a micro-meteorological interval, including Kolmogorov turbulence), represent the sums of spectrums of the separate coherent structures of the different sizes (with various outer scales).

Thus, in article, on the basis of gained by us earlier a frequency spectrum of single coherent structure in a micrometeorological interval of atmospheric turbulence, calculate expression for a spectrum of single coherent structure.

The sums of spectrums of coherent structures with various outer scales successfully approximate the experimental spectrums of atmospheric turbulence in a wide frequency band (including micro-meteorological, mezzo-meteorological and synoptic intervals). The results gained in the present work confirm and expand on the field of very low frequencies made earlier in our articles a conclusion that, despite their complex internal structure, coherent structures are a elemental components (fundamental particles) of atmospheric turbulence. It is shown that known experimental synoptic spectrums of really observable atmospheric turbulence (including spectrums of small-scale turbulence, the spectrum by Van ??? Hovena, 1957; the spectrum by Monin and Kolesnikova, 1965) represent the sums of spectrums of single coherent structures with the different sizes (with

various outer scales).

The authors are grateful to the Russian Foundation for Basic Research for financial support (grant no. 15-05-05404).

9910-76, Session PWed

ALMA array operation group process overview

Emilio Barrios, Hector Alarcon, ALMA (Chile)

ALMA observatory is a very complex interferometer consisting in 66 antennas, 4 different antennas model and 2 correlators installed on Llano de Chajnantor, at 5050 m altitude in the Chilean Andes. The complexity of the system is a particular challenge to engineers, scientists and operators alike.

Science operations activities in Chile are responsibility of the Science Operations Department, which consists of three groups: the Program Management Group, the Data Management Group and the Array Operations Group (AOG).

The Array Operation Group (AOG) consist in 10 operators, one Array operator group Manager and 1 deputy Manager. The group does provide support for Science Observations and to the day-to day engineering activities, in parallel with the observations, operating safely and efficiently the Interferometric Arrays, remotely from the Operation Support Facility at 2,950 meters Altitude.

They should follow the observatory goals and objectives yearly defined, the science and engineering coverage needs, the management and coordination agreements, the ALMA Safety and emergency rules, the weather conditions and the antenna operation policies and permissions.

AOG is responsible for operate the antennas and their instrumentation, ensure the correct execution of semiautomatic processes, monitor the antenna performance, the environmental and safety conditions, adjust the relevant system parameters accordingly, perform basic diagnosis and correction of problems that may arise during the work shift, prepare systems before the observation time and maintenance activities, execute and monitor the observations progress, report problems, and develop and maintain operational procedures and tools (checklist, internal communication flow, procedures updated, troubleshooting guide lines, scripts)

Array operators works in 8x6 turnos (7 effective shifts) providing 24 hrs coverage with 4 rotative shifts (Morning, Afternoon, Evening and Night). The AOG deputy is responsible to organize and consolidate the schedule among the Array Operators with at least one month in advance.

The Array Operator lead is the AOG Manager that supports the head of Science Operations in defining policies and procedures for ALMA science operations as well as in planning and coordinating science operations activities. Also organize and evaluate tests of the OMC software tool (operators interface to the control system), Shiftlog, Problem Reporting System, Alarms System, and Logging System.

The purpose of the Poster is to show an overview of the Array Operation process, group management and tools used in the context of the Science Operation Observations.

9910-77, Session PWed

System-dependent earthquake inspection procedures at Paranal Observatory

Juan Osorio, Andres Ramirez, European Southern Observatory (Chile)

Paranal Observatory is located near Antofagasta city, northern Chile , one of the most seismic regions in the world. Telescopes and scientific instruments are permanently exposed to the risk of damage caused by earthquake events, ranging from optical misalignment to complete cease of operations. A seismic monitor is installed on the site, providing real-time data to make rapid post-earthquake assessments of expected damage and determine the areas, type and level of inspections to be carried out before continuing with the regular operations. With more than ten years of seismic data and its correlation with reported issues, we show that the inspection and recovery strategy can be defined taking into account the characteristics of the seismic event and according to system-dependent criteria.

9910-78, Session PWed

SystMon: a data visualization tool for the analysis of telemetry data

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The Paranal Very Large Telescopes (VLT) Observatory is a complex multifunctional observatory where many different systems are generating telemetry parameters. As systems becoming more and more complex, also the amount of telemetry data is increasing. This telemetry data is usually saved in various data repositories. In order to obtain a full system overview, it is necessary to link all that data in a meaningful and easy to interpret way. A step forward from simple telemetry data visualization has been done by developing a new tool that can combine different data sources and has a powerful graphing capability. This new tool, called SystMon, is developed in iPython an interactive-web browser environment under the philosophy of notebooks which combine the code and the final product. The application can be shared among other colleagues and having the code side by side gives the accessibility to inspect and review the process improving and adding new capabilities to the application. SystMon allows to manipulate, generate and visualize data in different types of graphs and also to create directly statistical reports. SystMon helps the user to model, visualize and interpret telemetry data in a web-based platform for monitoring the health of systems, understanding short- and long-term behaviour and to anticipate corrective interventions.

9910-80, Session PWed

Obsolescence of electronics at the VLT

Gerhard Hüdepohl, Juan Pablo Haddad, European Southern Observatory (Chile)

The ESO Very Large Telescope Observatory (VLT) at Cerro Paranal in Chile had its first light in 1998. Most of the telescopes electronics components were chosen and designed in the mid 90s and are now around 20 years old. This leads to the problem of increasing failure rates due to aging and lack of spare parts, as many of them are no longer available on the market.

The lifetime of large telescopes is generally much beyond 25 years. Therefore the obsolescence of electronics components and modules forces the operations teams to upgrade the systems to new technology.

This is a time and money consuming process, which often is not straightforward and has various types of complications.

This poster shows the analysis, approach, timeline, complications and progress in upgrades at the Paranal Observatory.

9910-81, Session PWed

Operation of AST3 Telescope and site testing at Dome A, Antarctica

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Astronomical Observatories (China); Yi Hu, Bin Ma, National Astronomical Observatories (China)

We have successfully operated the AST3 telescope remotely as well as robotically for time-domain sky survey in 2015. We have set up a real-time system to support the operation of the unattended telescope, monitoring the status of all instruments as well as the weather conditions. The weather tower also provides valuable information of the site at the highest plateau in Antarctica, demonstrating the extremely stable atmosphere above the ground and implying excellent seeing at Dome A.

The real-time monitoring system has a web-based interface displaying a picture of the site and the telescope taken with a webcam every hour. The observatory consists of the telescope, a CCD camera, an on-site Control, Operation and Data System (CODS), other small experiments, and an independent supporting system, PLATO-A, for power and communication. During the operation season, CODS ran many daemon programs and scripts in the background to collect information from different sources which is transferred back via Iridium satellites and then shown on our website in real-time. All data sampling rates can be customized remotely. We were able to show key status of the telescope, including various temperatures, voltages and currents, pointing and tracking, and focusing etc. We were also able to monitor the CCD camera temperatures and image quality in real-time. CODS collects information on its control computer, data storage system, and pipeline system as well. There is also an alarming system which, once triggered by any malfunction or pre-defined conditions, sends different SMS immediately to different people in charge. In addition, we have set up a 15-m weather tower with sensors at various heights for site testing as well as assisting the operation. It records very strong temperature inversion and stable atmosphere, especially in local winter, confirming what we have found in 2011 and indicating a very promising site for astronomical observations. Further data analysis will quantitatively evaluate the quality of the site as an astronomical observatory for large telescopes.

9910-82, Session PWed

Operations of the laser traffic control system in Paranal

Paula Santos, Paola Amico, European Southern Observatory (Germany); Douglas M. Summers, Large Binocular Telescope Observatory (United States); Philippe R. Duhoux, Robin Arsenault, Thomas Bierwirth, Harald Kuntschner, Pierre-Yves Madec, European Southern Observatory (Germany); Michael Pruemm, European Southern Observatory (Germany) and Informate (Germany); Marina Rejkuba, European Southern Observatory (Germany)

The Laser Traffic Control System (LTCS) of the Paranal Observatory is the first component of the Adaptive Optics Facility (AOF) to enter routine operations on the 1st of October of 2015. Its genesis dates back to the 2009 AOF final design review, when the need for a laser beam avoidance tool was recognised as the best way to support operations of an observatory equipped with four powerful lasers and a large number of laser-sensitive instruments.

After an initial review, the LTCS developed for Maunakea, and operated since 2002, became the tool of choice for the Paranal Observatory, provided it could be adapted to fit its operational model, in particular, interfacing with Paranal's observing tools.

LTCS-Paranal, now deployed and embedded in the Observatory's operational environment, provides the observers with real-time information about on-going collisions, predictive information for possible collisions, and priority resolution between telescope pairs, where at least one telescope is operating a laser. It supports: 1) high configurability of telescopes and instruments, in particular the frequent changes of station of the Auxiliary Telescopes on the VLT Interferometer platform; 2) right-of-way priority rules that support the different operational scenarios at the Observatory, namely mixed visitor and service mode nights (Q-scheduling), high priority observations (Target of Opportunity, Rapid Response Mode, etc.) and commissioning runs; 3) changes of laser constellation configurations, enabling to switch, even during a night, between single centrally propagated laser to the different available 4-laser constellations, typical for the AOF instruments such as MUSE and HAWK-I; 4) future laser-equipped telescopes (including the E-ELT) and 5) interfacing with ESO's observing tools, OT (Observing Tool) and vOT (visitor Observing Tool), for service and visitor mode observations.

The observing tools have been interfaced with the LTCS, tested and deployed at the observatory in March 2015. Since then, they offer laser collision detection features to the users. For each observation, information on possible collisions is obtained through HTTP get requests to the LTCS Query Server and suitably displayed in the graphical user interface. The tools also support laser sensitivity analysis, avoiding collision reports whenever the setup used for an observation is not sensitive to the laser.

While LTCS' displays and alarms cover the real-time operational scenario, the new laser collision detection features available in OT and vOT facilitate the short-term observation planning, informing the users of any laser collisions before starting an observation in a "what-if" scenario: "if I start this observation now, will there be any laser collisions?". Altogether, LTCS-Paranal and the observing tools allow the night operators to plan and execute their observations without worrying about possible collisions between the laser beam(s) and other laser-sensitive equipment, aiming at a more efficient planning of the night and, consequently, preventing time losses and laser-contaminated observations.

9910-83, Session PWed

NIRSpec pre-imaging

Leonardo Ubeda, Tracy Beck, Space Telescope Science Institute (United States)

Most observations with NIRSpec spectroscopy (such as all MSA observations, as well as crowded-field observations using the IFU and FS) will require high spatial resolution images of the science field previous to performing the spectroscopy. This is due to the fact that the standard NIRSpec target acquisition (TA) procedure needs to acquire reference stars with a position RMS of less than 20mas. NIRSpec TA uses 8-20 reference stars with accurate astromerty (<5mas) calculates centroids of the individual stars on the detector, transforms their pixel coordinate positions into positions on the sky, and iterates on the telescope pointing and slew until the position RMS of the reference stars is less than 20mas.

For some planned observations, very high spatial resolution HST images (either ACS/WFC or WFC3/UVIS/IR) might be already available and, in other cases, NIRCam observations will be performed.

For a planned NIRSpec observation, we describe in detail the proposed method to generate a high resolution mosaic of the NIRSpec field of view. We show the results of an example using existing HST/ACS observations and we also describe the proposed procedure using simulated NIRCam images. We also describe the creation of source catalogs. These two data products will be crucial for the success of most NIRSpec observations.

9910-84, Session PWed

Sun avoidance strategies at the Large Millimeter Telescope

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The Large Millimeter Telescope observatory is extending its night time operation to the day time. A sun avoidance strategy was therefore implemented in real-time in the control system to avoid excessive heating of the secondary mirror and the prime focus.

The LMT uses an “on-the-fly” trajectory generator that receives as input the target location of the telescope and in turn outputs a commanded position to the servo system. The sun avoidance strategy is also implemented “on-the-fly” where it intercepts the input to the trajectory generator and alters that input to avoid the sun. Two sun strategies were explored. The first strategy uses a potential field approach where the sun is represented as a “high-potential” obstacle in joint space and the target location is represented as a “low-potential” goal. The potential field is repeatedly calculated as the sun and the telescope move and the telescope follows the induced force by this field.

The second strategy is based on path planning using visibility graphs where the sun is represented as a polygonal obstacle in joint space and the telescope follows the shortest path from its actual position to the target location via the vertices of the sun’s polygon.

The visibility graph approach was chosen as the favorable strategy due to the efficiency of its algorithm and the simplicity of its computation.

9910-85, Session PWed

Observing with FIFI-LS on SOFIA: time estimates and strategies to use a field imaging spectrometer on an airborne observatory

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Observing on the Stratospheric Observatory for Infrared Astronomy (SOFIA) requires a strategy that takes the specific circumstances of an airborne platform into account. Observations of a source cannot be extended or shortened on the spot due to flight path constraints. Still no exact prediction of the time on source is available since there are always wind and weather conditions and sometimes technical issues. Observations have to be planned to maximize the observing efficiency while maintaining full flexibility for changes even during the observation.

The Field-Imaging Far-Infrared Line-Spectrometer (FIFI-LS) entered service on SOFIA in March 2014. Up to November 2015 it has completed 24 commissioning and science observing flights. The instrument features two parallel spectral channels with wavelength ranges of ~51?m to ~120?m and ~115?m to ~203?m respectively. Each channel has a field of view of 5 by 5 spatial pixels with a size of 6”/pixel in the short wavelength channel and 12”/pixel in the long wavelength channel. The spectral resolution of the instrument is in the range of R=~1000 to ~2000. With its combination of wavelength range, resolution and imaging capabilities FIFI-LS is designed specifically for the investigation of the interstellar medium in our own and other galaxies.

The complex nature of observations with FIFI-LS, e.g. the interlocking cycles of the mechanical gratings, telescope nodding and dithering, is considered in the observing strategy as well. Starting with SOFIA Cycle 3, FIFI-LS is available to general investigators. Requested observations are planned in a standardized way. One must be able to define the needed parameters simply, without being familiar with the instrument. These parameter sets will still result in efficient observations and have all the information for the inflight team to maximize the science output as boundary conditions change.

In this poster/paper we will describe the observing process with FIFI-LS from the integration time estimate and the mapping area to the actual observation performed in flight. This includes an overview of the observing scenarios that have proven to be useful for FIFI-LS. Using typical FIFI-LS observations, we show how observations are laid out. This will include:

• mapping of bright and faint sources including spatial redundancy due to the challenging calibration of far infrared measurements,

• how the required spectral coverage and redundancy affect the observing efficiency and strategy,

• how to efficiently distribute observations of the same target over multiple flights,

• how to implement observatory specific features e.g. “line of sight rewinds” into the observations while keeping the observations flexible until the commence for consortium as well as for general investigator targets,

• how the performance parameters of the SOFIA telescope lead to certain observing modes that are efficient yet still flexible.

9910-86, Session PWed

High precision tracking method for solar telescope

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A high-precision real-time tracking method for solar telescope was introduced, this method was based on the full-disk solar image barycenter algorithm. To make sure the calculation of the barycenter was accurate and reliable, a series of strict logic limits were set, such as the gray threshold, the range limit of the barycenter displacement and its deviation from a perfect disk. So we could eliminate noise caused by bad weather, such as clouds and fog, and located the barycenter of the full-disk solar images which recorded by large array CCD in real time robustly. The barycenter displacements detection and the telescope axis control formed an automatic close loop and realized the high precision tracking. An Ethernet interface was also provided for remote control. In the observation, the precision of this new method was better than 1?/30 minutes.

9910-87, Session PWed

ESO Phase 3 automatic data validation: groovy-based tool to assure the compliance of the reduced data with the science data product standard

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The ESO Phase 3 infrastructure provides a channel to submit reduced data products for publication to the astronomical community and long-term

data preservation in the ESO Science Archive Facility. To be integrated into Phase 3, data must comply with the ESO Science Data Product Standard in terms of format and metadata. For this purpose ESO has developed a new Groovy based tool that carries out an automatic validation of the reduced products triggered when data are submitted.

Here we present the structure of the tool and the checks that are implemented. The rules involved are organized in a hierarchical way and grouped in sets in order to perform a validation customized to the different type of products, for example image, spectrum, catalogue, IFU cube, etc.

9910-88, Session PWed

Automated scheduler improvements and generalizations for the Automated Planet Finder

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The Automated Planet Finder (APF), designed as a single purpose facility to search for exoplanets, has become a general use observatory that is used by observers the world over. We describe the improvements of our software for operations to both optimize work for finding planets and supporting a much broader community of astronomers with a variety of interests and requirements. These include a variety of observing modes beyond the originally envisioned fixed target lists, such as time dependent priorities to meet the needs of rapid varying targets, and improved tools for simulating observing cadence for the planet hunting teams. None of the changes resulted in lost observing time, and were implemented by the only permanent staff member for the APF. The of implementation of these additions illustrates the power and flexibility of the underlying software infrastructure.

9910-89, Session PWed

Trends and developments in VLT data papers as seen through telbib

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The ESO Telescope Bibliography (telbib) is a database of refereed papers published by the ESO users community. It links data in the ESO Science Archive with the published literature, and vice versa. Developed and maintained by the ESO library, telbib also provides insights into the organization's research output and impact as measured through bibliometric studies.

Numerous reports, statistics, and visualizations derived from telbib help to understand the way in which the user community uses ESO/VLT data in publications. Based on selected use cases, this contribution will showcase recent trends and developments.

9910-90, Session PWed

Optimizing the observational efficiency of the Southern African Large Telescope (SALT) using dynamic scheduling

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The Southern African Large Telescope (SALT) is a fully queue schedule telescope. Observations are executed using observing blocks which contain target and instrument configuration information. Observing blocks are assigned priorities by principle investigators according to the scientific priority categories assigned to the program by the time allocation committee. The dynamic scoring algorithm used by the SALT Operations Team aims to maximize the number of high priority observing blocks completed during an observing semester.

There are a number of static parameters in the dynamic scoring algorithm. The priority of blocks are converted to a score, as are the program-internal rankings supplied by the PI. Since SALT time is allocated by consortium partner shares, an adjustment is made to the score based on how much time the partner in question has received to date.

Dynamic parameters in the algorithm aim at taking into account the likelihoods of getting an observation done as well as the completeness of programs. i.e. the aim is to observe those blocks first which are disappearing first, those with more stringent Moon and Seeing conditions, as well as completing visits to a given target already started, not to waste observing time in partial observations. Object availability is determined from the total number of nights a target is still visible during the remainder of the semester. Completeness of blocks and programs are simply calculated by summing up the time in accepted blocks vs. the allocated times. These schemes also take into account monitoring programs with repeated visits necessary over a given time, as well as pools of optional targets.

The aim of the scoring algorithm is to give the observer and indication which block would be most efficient to observe at the given time to maximize the high-priority block completeness over the whole semester. Previously, the SALT Astronomer made these decision based solely on the present conditions and the scientific priority of the blocks available at the given time.

We discuss the limitations and future development of the algorithm. At present, the scheduling essentially follows a greedy search algorithm. It is the best solution for changing conditions since one only considers the next available target, although it is not necessarily the optimal global solution for a whole night. Rapidly changing weather conditions and unpredictable mirror alignments make it difficult to schedule a whole night. However, the present algorithm already can be used effectively by using it to recreate the queue during the night as conditions change.

Finally, we discuss development of semester long simulations of the SALT observing queue, and how it has represented actual observations during the latter half of 2015. We also have given the PIs tools to estimate the probabilities of getting their observations done with the constraints that they define for the blocks.

9910-92, Session PWed

Large collaboration in observational astronomy: the Gemini Planet Imager exoplanet survey case

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The Gemini Planet Imager (GPI) is a next-generation high contrast imager constructed for the Gemini Observatory. It is one of the most advanced planet-imaging systems in operation – an order of magnitude more sensitive than any previous AO systems, capable of detecting and spectroscopically characterizing young Jovian planets 106 times fainter than their parent star at separations of 0.5 arcseconds as well as studying debris disks.

Our team initiated the GPI Exoplanet Survey (GPIES) in November 2014. Our goal is to observe ~600 stars in 850 h of telescope time in three years to look for young Jupiter-like exoplanets and debris disks. The team includes ~90 researchers from ~35 institutions located mostly in North and South America, a rather unique case in ground-based astronomy but probably the future of all major instrumentation-based survey in astronomy. Significant efforts, including a task-oriented structure of the team, a detailed campaign policies and data rights document will be described. Our team focused on using modern communication tools (wiki website, project management, telecon, mailing lists, shared documents), optimized scheduler and data processing pipelines (data sharing, several algorithms to search for planets and disk). Our goal is to optimize operation management and improve the technical and scientific productivity of this campaign while maintaining its cost. We will describe lessons learned, progress made and future ideas to conduct such long-term surveys in collaboration with large telescope observatories.

9910-93, Session PWed

Data reduction pipelines for the Keck Observatory archive

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The Keck Observatory Archive (KOA) currently serves 40 TB of data spanning over 20 years from all ten past and current facility instruments at Keck.

Although most of the available data are in the raw (level-0) form, one of KOA's goals is to produce quick-look, browse reduced (level-1) products for all of the instruments so that users can better assess the scientific content and quality of the data.

It is necessary to develop completely hands-off, automated data reduction pipelines (DRPs) for this purpose. Our approach is to adapt existing pipelines and algorithms where possible, and use languages that do not require special environments or commercial licenses, in order to maximize their utility and usefulness to the user community as well.

We describe what level-1 data products are currently available in KOA, review the existing reduction tools for Keck data, and present our plans and anticipated priorities for the development of automated DRPs and release of reduced data products for the current and future instruments in KOA. In addition to the raw data, KOA currently serves quick-look, level-1 products generated by automated pipelines for four instruments (HIRES, NIRC2, OSIRIS, LWS).

KOA underwrote the update of the MAKEE software to support reduction of the CCD upgrade to HIRES, developed scripts for reduction of NIRC2 data and automated the existing OSIRIS and LWS data reduction packages. We recently completed the development of a fully automated pipeline written in Python for NIRSPEC. This DRP will be used to create level-1 products for KOA, and made available for use by the community through open source repositories such as Github. The challenges encountered in designing this pipeline include fully automating the wavelength calibration, which was solved by using an algorithm that performs a two-dimensional fit to sky lines. We also anticipate that Keck's newest instrument NIRES, which will be delivered with a fully automated DRP, will be the first to have both raw and level-1 data ingested at commissioning.

9910-94, Session PWed

HIRES the high resolution spectrograph for the E-ELT: integrated data flow system

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The current E-ELT instrumentation plan foresees a High Resolution Spectrograph conventionally indicated as HIRES whose Phase A study will start in 2016. An international consortium (called the "HIRES initiative") is conducting a a preliminary study of a modular E-ELT instrument able to provide high-resolution spectroscopy (R~100,000) in a wide wavelength range (0.37-2.5 ?m). For the aims of data treatment (which encompasses both the reduction and the analysis procedures) an end-to-end approach has been adopted, to directly extract scientific information from the observations with a coherent set of interactive, properly-validated software modules. This approach is favoured by the specific science objectives of the instrument, which pose unprecedented requirements in terms of measurement precision and accuracy. In this paper we present the architecture envisioned for the HIRES science software, building on the lessons learned in the development of the data analysis software for the ESPRESSO ultra-stable spectrograph for the VLT (currently at the integration phase).

9910-95, Session PWed

Aircraft avoidance for laser propagation at the Large Binocular Telescope Observatory: life under a busy airspace

Gustavo Rahmer, Julian C. Christou, Michael J. Lefebvre, Large Binocular Telescope Observatory (United States)

A key aspect of LGS operations is the implementation of measures to prevent the illumination of airplanes flying overhead. The most basic one is the use of "aircraft spotters" in permanent communication with the laser operator. Although this is the default method accepted by the FAA to authorize laser propagation, it relies on the inherent subjectivity of human perception, and requires keeping a small army of spotters to cover all the nights scheduled for propagation.

Following the successful experience of other observatories (Keck and APO), we have installed an automatic aircraft detection system developed at UCSD known as TBAD (Transponder-Based Aircraft Detection). The system has been in continuous operation since April 2015, collecting detection data every night the telescope is open.

We present a description of our system implementation and operational procedures. We also describe and discuss the analysis of the TBAD detection data, that shows how busy our airspace is, and the expected impact on the operation efficiency of the observatory.

9910-96, Session PWed

Genetically optimizing weather predictions

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For the past ~7 years the Southern African Large Telescope (SALT) has archived its live weather data (temperature, humidity, air pressure, wind speed and wind direction). Built upon this database, we have developed a remarkably simple approach to derive a functional weather predictor. The aim is to provide up to the minute local weather predictions in order to prepare dome environment conditions ready for night time operations or plan, prioritise and update weather dependent observing queues.

We take the current live weather readings, then search the entire archive for similar conditions. Predictions are made against an averaged, subsequent 24 hours of the closest matches for the current readings. We use Genetic Programming and Genetic Algorithms to optimise our formula through weighted parameters.

The accuracy of the predictor is routinely tested and tuned against the full, updated archive to account for seasonal trends and total, climate shifts.

The live (updated every 5 minutes) SALT weather predictor can be viewed here:

http://www.saao.ac.za/~sbp/suthweather_predict.html

9910-97, Session PWed

Opto-mechanical design of a deployable tertiary mirror for the Keck I telescope

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The new deployable tertiary mirror for the Keck I telescope at the W. M. Keck Observatory presents unique challenges for opto-mechanical design. The mirror needs to either reflect the beam to one of six positions around the telescope elevation ring or retract out of the way to allow the use of Cassegrain instruments. At the same time, the in-beam pointing of the mirror must be repeatable to less than 11.5 arcseconds. This paper addresses the mechanical designs developed to meet these functional requirements. One key consideration is gravitational deformations of the mirror support structure. Since gravitational forces vary with telescope orientation, we performed extensive analyses where deformation and mirror pointing error are predicted to confirm that pointing can meet requirements with a non-vignetting instrument profile.

To achieve a non-vignetting profile, the mirror assembly, which exceeds 100 Kg, has to retract into a narrow 300mm thick volume outside of the Cassegrain field of view and inside the shadow of the M1 to M2 optical path. To address the repeatability of mirror pointing, we use kinematic mechanisms for deployment positioning, mirror azimuth positioning and mirror assembly mounting. The repeatability of the kinematic coupling was confirmed with a test bed. The use of high precision displacement sensors showed that our position repeatability at each kinematic interface was less than 2 microns. We are currently in the detailed design phase of this project. Construction will follow with installation at the observatory approximately 1 year later.

9910-99, Session PWed

DAG telescope site studies and infrastructure for possible international co-operations

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The selected site for the 4 m DAG (Eastern Anatolian Observatory in Turkish) telescope is “Karakaya Tepeleri”, at 3170m altitude. The telescope’s optical design is performed by the DAG technical team to allow infrared observation at high angular resolution, with its adaptive optics system to be built in Turkey. In this paper; a brief introduction about DAG telescope design; planned instrumentation; the meteorological data collected from 2008, clear night counts, short-term DIMM observations; current infrastructure to hold auxiliary telescopes; auxiliary buildings to assist operations; the observatory design; and coating unit plans will be presented along with potential collaborations in terms of instrumentation and science programs.

9910-100, Session PWed

An autonomous observation and control system of BSST in Antarctic

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Many astronomy telescopes are built in remote sites such as high altitude plateau and mountain, Antarctic, and outer space, because they offer better seeing, less atmospheric water vapour, and reduced light pollution. But these areas are not suitable for human habitation for its harsh environments. Hence the ability of autonomous observation and control for astronomical telescope is highly required. This paper describes the design of an Antarctic autonomous observation and control system with remote operation, which is aimed at the Antarctic Bright Star Survey Telescope (BSST) which will be built in 2016 at Zhongshan Station, Antarctic.

BSST is a small telescope with 30cm aperture, which is used to study extrasolar planet. Its field of view is wide, so it can observe many targets simultaneously, which has advantage of bright star survey. After its construction, BSST will take advantage of polar night to make observation on wide scope sky area.

An EPICS (Experimental Physics and Industrial Control System) and RTS2(Remote Telescope System, 2nd Version) based autonomous observation and control system with remoted operation is designed for BSST. EPICS is a set of Open Source software tools, libraries and applications developed collaboratively and used worldwide to create distributed soft real-time control systems for scientific instruments while RTS2 is an open source environment for control of a fully autonomous observatory. Using the advantage of EPICS and RTS2 respectively, a combined integrated software framework for autonomous observation and control is established that use RTS2 to fulfill the function of astronomical observation and use EPICS to fulfill the device control of telescope.

The structure of the autonomous observation and control system for telescope in Antarctic is designed and developed based on RTS2 and EPICS. Observation control models are designed based on RTS2. A command and status interface for EPICS and RTS2 is designed to make the EPICS IOC (Input/Output Controller) components integrate to RTS2 directly. For the specification and requirement of control system of telescope in Antarctic, core components named Executor and Auto-focus for autonomous observation is designed and implemented with remote operation user interface based on Browser-Server mode.

To realize autonomous observation of BSST, we investigate the need of observation and define several observation mode and observation plan. Executor can automatically load plans from database and execute them. Status Monitor and alarm mechanism is designed for the automatic control of telescope.

The whole system including the telescope is tested in Lijiang Observatory in Yunnan Province for practical observation to complete the autonomous observation and control, including telescope control, camera control, dome control, weather information acquisition with the local and remote operation.

9910-101, Session PWed

Education and public engagement in observatory operations

Pavel Gabor, Vatican Observatory Research Group (United States); Louis Mayo, NASA Goddard Space Flight Ctr. (United States); Dennis Zaritsky, The Univ. of Arizona (United States)

Education and public engagement (EPE) is an essential part of astronomy's mission. New technologies, remote observing and robotic facilities are opening new possibilities for EPE. A number of projects (e.g., NASA-sponsored Global Telescopes In Education, UNC's Skynet) have developed new infrastructure, a number of observatories (e.g., University of Arizona's "full-engagement initiative" towards its astronomy majors, Vatican Observatory's collaboration with high-schools) have dedicated their resources to practical instruction and EPE. Some of the facilities are purpose built, others are legacy telescopes upgraded for remote or automated observing. Networking among institutions is most beneficial for EPE, and its implementation ranges from informal agreements between colleagues to advanced software packages with web interfaces. The deliverables range from reduced data to time and hands-on instruction while operating a telescope. EPE represents a set of tasks and challenges which is distinct from research applications of the new astronomical facilities and operation modes. In this paper we examine the experience with several EPE projects, and some lessons and challenges for observatory operation.

9910-102, Session PWed

Monitoring the performance of the Southern African Large Telescope

Christian Hettlage, Chris Coetzee, Petri Vaisanen, Encarni Romero Colmenero, Steven M. Crawford, Paul Kotze, Paul Rabe, South African Astronomical Observatory (South Africa) and Southern African Large Telescope (South Africa); Stephen Hulme, Southern African Large Telescope (South Africa); Janus Brink, Deneys S. Maartens, Keith R. J. Browne, Ockert Strydom, South African Astronomical Observatory (South Africa) and Southern African Large Telescope (South Africa); David De Bruyn, Amazon (South Africa)

The efficient running of a telescope requires both engineers and scientists to be aware of operational successes and problems on a daily and on a long-term basis. In this paper the authors present the Fault Tracker, Nightlogs and Dashboard, which achieve this goal for the Southern African Large Telescope (SALT).

Most operational errors are automatically entered into the SALT database by the telescope control software along with the relevant details like subsystem, time of occurence and severity. The list of faults can be viewed for a user-selected night via a web-based interface called the Fault Tracker (FT). The FT also gives the user access to the full details of individual faults.

Users can add new, edit existing and comment on faults in the FT. Previous revisions of faults are kept in the database.

In order to allow for easier classification of faults the FT allows tags to be added to faults either manually or automatically based on the affected subsystem or an error code.

The SALT Astronomer and SALT Operator use their Nightlogs to record the weather details, engineering time and telescope downtime throughout the night, and this information is automatically entered into the database.

All this allows SALT's efficiency to be measured by various metrics like technical and weather downtime, observation efficiency and number of observations. These are collectively displayed by another web-based interface called the Dashboard for the last night, the last week, the last 31 nights, the last six months and the semester to date.

Depending on the time period and metric, bar charts, dials, pie charts or line charts are used. Colour coding (red, yellow, green) is employed to show whether the value for a metric is within the required range. Trend curves are included with the bar charts.

In order to maintain awareness and encourage discussions about SALT's operational status, the Dashboard offers a kiosk mode which rotates through slides with the plots of key metrics. This is displayed on a public screen at the telescope in Sutherland and at the South African Astronomical Observatory in Cape Town.

Most of the tools are browser-based single page applications, using libraries and frameworks like jQuery, AngularJS and D3. Flask is used to provide the server-side API functionality. The data are stored in a MySQL database. The merits and drawbacks of the libraries as well as possible applications for other telescopes are discussed.

9910-103, Session PWed

Gaia uplink commanding system at work: VPU SW on-board commissioning

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Gaia is a spinning spacecraft designed to observe every star in the magnitude range G = [3.0 - 20.0], being partially complete only on very high-density areas of the sky. It will create the most detailed 3D map of the Galaxy, comprising a billion stars.

The Gaia observes using two telescopes sharing a common focal plane. This Focal Plane Array (FPA) comprises 106 CCDs aligned in 7 rows and 17 functional strips. Each of the 7 CCD rows is controlled by one Video Processing Unit (VPU) that operates each CCD in TDI mode synchronized with the spacecraft's 6-hour spin period around its z-axis.

The observation strategy is defined by a scanning law and the configuration of the VPUs. The scanning law describes the attitude of the spacecraft as a function of time. The VPUs are hybrid microprocessor-FPGA systems in charge of detecting, confirming and observing any object crossing the focal plane in the nominal magnitude range. The VPU algorithms are highly parametrized so their behaviour is highly customisable.

The Gaia uplink commanding system's main tasks are to generate the commanding to modify the configuration of the VPU parameters on-board, properly schedule each parameter modification and maintaining a CDB (Configuration Data Base) on-ground with all those configurations timestamped per VPU.

The input to the Gaia uplink commanding system is the calibration activity. The commanding of an activity is based on a set of fixed templates comprising consecutive time-stamped telecommand sequences. Only a subset of the sequences defined in the Operations Data Base (ODB) are used: VPU memory patches, EEPROM patches, dumps and dump-checksums, Service Interface Function (SIF) and VPU mode changes (service, operational, used/unused by the Attitude and Orbit Control System). The template is filled using 'calibration activity data sets', containing the VPU memory patches. The scheduler operation is thus limited to program the execution of a given template and data set at a particular time. A Payload Operations Request (POR) file is then produced and sent to the Mission Operations Centre (MOC) for uplink and execution on-board. In addition, a record of the transaction and any patched data is stored in the CDB for its consumption by the Data Processing and Analysis Consortium (DPAC).

During the nominal mission the VPU algorithms software were updated on-board to include new capabilities. All those new capabilities were tested, commissioned and optimised. Intense commanding to modify the VPU parameters in a limited period of time was required. All the calibrations and tests were performed using the Gaia uplink commanding system.

In this talk, the key elements of the Gaia uplink commanding system will be illustrated using an example that took place during the Commissioning phase of the spacecraft, in which a new software version of the VPUs on-board Gaia. The full process of an activity generation to its commanding, the tools and restrictions imposed to the scheduling, telecommand budget and configuration maintenance will be explained through this example. Finally, the lessons learned for future survey missions will be discussed.

9910-104, Session PWed

Data flow operations and quality control of SPHERE

Wolfgang Hummel, European Southern Observatory (Germany); Julien H. V. Girard, Julien Milli, Zahed Wahhaj, European Southern Observatory (Chile); Lars Lundin, European Southern Observatory (Germany); Arthur Vigan, European Southern Observatory (Chile) and Lab. d'Astrophysique de Marseille (France)

ESO operates since April 2015 the new planet finder instrument SPHERE with three partly simultaneously operating arms supported by a common path coronograph with extreme AO. Observing modes include differential beam imaging, long slit spectroscopy, IFS and high contrast polarimetry. We report on the implementation of the SPHERE dataflow and quality control system and operational highlights in the first year of operations: This includes some unconventional parts of the SPHERE calibration plan like attached science observations, special rules for the selection of filters and the measures for an optimized calibration of the two polarimetric channels of the ZIMPOL arm. Finally we report on the significance of SPHERE quality control system, its relation to the data reduction pipeline and which unreported instrumental features have been revealed so far.

9910-106, Session PWed

Development of QuickPhot: an automated data acquisition and processing pipeline for observing AGNs

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This reports the development of "QuickPhot", an automated data acquisition and reduction pipeline. Cork Institute of Technology – Blackrock Castle Observatory (CIT-BCO) operates two nodes of remotely operated robotic telescopes based in California, US and Cork, Ireland. The observatories have been installed by BCO labs and are primarily used as a tool to facilitate STEM promotion (Project TARA) and as a testbed for automation and instrumentation. The node at BCO consists of two optical telescopes – 6" and 16" OTAs housed separately while the one at California is its 6" replica. QuickPhot is an automated data reduction pipeline aimed at studying the microvariability of blazars. The telescopes constantly monitor the skies in search of optical photometric variability in predefined targets whenever observing conditions are favourable. After carrying out aperture photometry, if any interesting behaviour is observed, the telescopes report the source and follow up with multi band observations using one or more nodes that are located in strategically separated timezones for continuous monitoring of astrophysical phenomenon.
We investigate the conformance of Shock-in-jet and the Geometric models, which try to explain the processes at work in AGNs which result in the formation of jets, by looking for temporal variability in these 2 band observations. Two-channel Optical PHotometric Imaging CAMera (TO?CAM) has been optimised for two band photometry on 16" OTA using two 1k ? 1k EMCCDs. Plans are underway for mounting TO?CAM on a larger OTA for precision photometry which may use LuckyPhot to further improve results by doing away limitations posed by atmospheric disturbances. The Telescope ARrAy (TARA) nodes work in conjunction with TO?CAM as one system to examine the most appropriate model interpreting the optical variability exhibited by AGNs by searching for variability and carrying out precision photometry continuously in an automated mode.

9910-107, Session PWed

Taking the San Pedro Martir National Astronomical Observatory into the era of time domain and massive data astronomy

Mauricio Reyes-Ruiz, Joel Castro, Enrique Colorado, David Hiriart, Elena Jimenez, William H. Lee, Manuel Nunez, Michael G. Richer, Alan M. Watson, Univ. Nacional Autónoma de México (Mexico)

We present the operational measures taken and the infrastructure recently constructed and under development at the Observatorio Astronomico Nacional in San Pedro Martir, Mexico (OAN-SPM), to equip it in order to address the challenges of time domain astronomy and the handling of large amounts of data resulting from wide field, high cadence observations.

These include the construction of infrastructure for high bandwidth data transmission to the observatory via fiber optics, and the installation or upgrade of 5 new robotic, meter-class telescopes to study a wide range of problems, from Kuiper Belt occultations (TAOS-2) to GRB followup (RATIR and GFT). In addition, several smaller aperture, robotic telescopes, dedicated to rapid follow-up of transient phenomena (BOOTES-5), diffraction limited imaging (COATLI) and very wide field observations (DDOTI), are currently being constructed. The design and construction of massive data storage facilities to host the results of these projects, reaching 1 PB in the next few months, and its integration with the OAN-SPM, are also discussed.

9910-108, Session PWed

Versatile quality control scheme for the adaptive optics instruments at the VLT

Julien H. V. Girard, European Southern Observatory (Chile)

The Paranal Observatory and its large instrument suite is unique in the world and leader in ground-based astronomy. There are many Adaptive Optics (AO) fed instruments on Paranal and more to come. To monitor their performances and assess the quality of the scientific data, we have developed a scheme and a set of tools and metrics adapted to each flavour of AO and each data product. Our decisions to repeat observations or not depends heavily on this immediate quality control "zero" (QC0). Atmospheric parameters monitoring can also help predict performances . At the end of the chain, the user must be able to find the data that correspond to his/her needs translated into a set of requirements based on simulations done with an exposure time calculator (ETC). Predictions and real performances must match and the assessment must be intelligible to the community. We will emphasis on the difficulties encountered to perform quality control with SPHERE and the need for different metrics at various levels of wavefront: i.e Strehl ratio and FWHM for SCAO/LTAO/MCAO, contrast for an xAO, EE for GLAO, etc.

9910-110, Session PWed

Model-based fault detection and diagnosis in ALMA subsystems

José L. Ortiz, ALMA (Chile); Rodrigo Carrasco, Univ. Adolfo Ibañez (Chile); Jaime Fariña, ALMA (Chile)

The Atacama Large Millimeter/Submillimeter Array (ALMA) observatory, with its 66 individual radiotelescopes and other central equipment, generates a massive set of monitoring data every day, collecting information on the performance of a variety of critical and complex electrical, electronic and mechanical components. This data is crucial for most troubleshooting efforts performed by engineering teams. More than 5 years of accumulated data and expertise allow for a more systematic approach to fault detection and diagnosis. This paper presents model-based fault detection and diagnosis to support corrective and predictive maintenance in an 24/7 minimum-downtime observatory.

9910-111, Session PWed

Investigating the effect of atmospheric turbulence on mid-IR data quality with VISIR

Mario van den Ancker, European Southern Observatory (Germany); Daniel Asmus, European Southern Observatory (Chile); Christian Hummel, Hans-Ulrich Käufl, Florian Kerber, European Southern Observatory (Germany); Alain Smette, European Southern Observatory (Chile); Julian Taylor, European Southern Observatory (Germany); Konrad Tristram, European Southern Observatory (Chile); Jakob Vinther, Burkhard Wolff, European Southern Observatory (Germany)

Accurately predictions of image quality -- typically taken as the FWHM of an unresolved point-source -- which can be achieved under a range of atmospheric conditions is an important prerequisite for queue-based scheduling at modern observatories. However, investigations of the relation between seeing at different wavelengths has so far been limited to wavelengths between 0.36 to 4.5 microns. Here we extend the relation between optical seeing and mid-infrared (7.8-19.5 micron) image quality using data from VISIR, the mid-infrared imager and spectrometer at ESO's Very Large Telescope. We find that the equations used so far to estimate mid-IR data quality from the optical seeing under-estimate the effect of atmospheric turbulence in the N-band (7-13 microns). We explore several options to align model predictions with the achieved mid-IR image quality. Adopting a larger outer length scale for the median atmospheric turbulence for Cerro Paranal than the so far adopted value of 23 m improves the agreement between measured and predicted image quality for VISIR, while it only has a modest effect on the predicted image quality at shorter wavelengths.

9910-112, Session PWed

Dispatch scheduling to maximize exoplanet yield

Samson Johnson, Harvard-Smithsonian Ctr. for Astrophysics (United States) and Univ. of Montana (United States); Nate McCrady, The Univ. of Montana (United States)

The MINiature Exoplanet Radial Velocity Array (MINERVA) is a dedicated exoplanet survey using radial velocity measurements of nearby (< 75 pc) stars to detect small planets. MINERVA will be a completely robotic facility, with a goal of maximizing the number of exoplanets detected. This requires a unique application of dispatch scheduling due to its automated nature and the requirement of high cadence observations. A dispatch scheduling algorithm is employed to create a dynamic and flexible selector of targets to observe, in which stars are chosen by assigning values through a weighting function. I designed and have begun testing a simulation which implements the functions of a dispatch scheduler and records observations based on target selections through the same principles that will be used at the commissioned site. These results will be used in a larger simulation that incorporates weather, planet occurrence statistics, and stellar noise to test the planet detection capabilities of MINERVA. This will be used to heuristically determine an optimal observing strategy for the project. The high precision RV spectrograph (1m/s) is being commissioned in the winter of 2015, and the results will be compared to the intentions of the implementation to this point. The choreography of the entire robotic site will also be commented on.

9910-113, Session PWed

DAG: a new observatory and a prospective observing site for other potential telescopes

Cahit Yesilyaprak, Atatürk Üniv. (Turkey); Sinan Kaan Yerli, Middle East Technical Univ. (Turkey); Onur Keskin, Isik Üniv. (Turkey)

DAG (Eastern Anatolian Observatory in Turkish) is the newest and largest (4 m) observatory of Turkey with the optical and near-infrared telescope and its robust observing site infrastructure. This national project consists of three phases: DAG: Telescope, Enclosure, Buildings and Infrastructures; FPI: Focal Plane Instruments and Adaptive Optics; and MCP: Mirror Coating Plant. The Ministry of Development of Turkey and Atatürk University supports all three phases. The tenders of telescope and enclosure have been completed in 2014 and 2015, respectively. The final design of telescope and building and almost all the infrastructure (roads, geological and atmospherical surveys, electricity, fiber optics, cable car, water, generator, etc.) of DAG site (which is at an altitude of 3,170 m in Erzurum/Turkey) have been completed. This poster is about the recent developments of DAG and about the future possible collaborations for various telescopes which can be constructed at the DAG site.

9910-114, Session PWed

FACT: from remote to robotic operation of an Imaging Atmospheric Cherenkov Telescope

Dominik Neise, ETH Zürich (Switzerland)

The First G-APD Cherenkov Telescope (FACT) is installed at the Canary island La Palma. Since Summer 2012, it is the first Imaging Atmospheric Cherenkov Telescope (IACT) being operated remotely without the need for data-taking personnel on site.

In order to achieve a robust and reliable remote operatable system, reliable monitoring and control of all subsystems is a necessity.

All components of FACT, including the drive, power supplies, trigger and data acquisition system as well as auxiliary systems are connected via the same layer of interprocess communication. The homogeneity of the communication layer by the Distributed Information Management System (dim) developed at CERN greatly simplifies operation.

In case of emergencies like complete power loss or sudden loss of network connection, it is agreed that the crew of the nearby MAGIC telescopes can be contacted for help.

Due to the large mirror area intrinsic to an IACT, the highest risk poses a nonfunctional drive system, leaving the telescope pointing towards the sun.

In such case, it is possible to park the telescope manually in less than 10 minutes.

Over time, the system was converted from a remotely operated to a remotely monitored Cherenkov observatory. This includes two distinct tasks.

First, the operation of each subsystem must be monitored and actions being taken in case of any malfunction. The low-level software or firmware does react in case of any parameter being outside predefined limits and takes necessary actions to bring the subsystem into a safe state or restart the operation. In rare cases, the situation has to be investigated by the shifter and experts on call.

The second task is taking physics data as well as special data for monitoring the performance of the full system.

The nightly observation schedule and technical runs are defined in advance and stored in a dedicated database.

The main physics task of FACT is the monitoring of a set of extragalactic sources of very high energy gamma-rays. In case of bright flaring activity of such a source, alerts have to be sent to the community as soon as possible.

Currently, the shifters role during the observation consists of monitoring the system status, visual inspection of the night sky conditions using all-sky cameras and additional weather input as well as examining the sources flux state. An inclusion of all-sky camera images into an autonomous weather condition assessment based on computer vision techniques is currently being developed.

To reduce the load on humans, an automatic alert system has been developed and is currently being tested by running it in parallel to remote operation by a shifter. In case of any malfunction or of a flare of the observed source, phone calls to a predefined list of people are initiated. To reduce single points of failure in such a safety related task as much as possible, a similar but independent second system is currently under development.

We will present the implementation of and experience from the remote and robotic operation of FACT from the past four years of successful operation.

9910-116, Session PWed

JWST guide star pipeline data products

Daryl A. Swade, Howard A. Bushouse, Pierre Chayer, Edmund P. Nelan, Space Telescope Science Institute (United States)

Science data products for James Webb Space Telescope (JWST) observations will be generated by the Data Management Subsystem (DMS) within the JWST Science and Operations Center (S&OC) at the Space Telescope Science Institute (STScI). A Guide Star Pipeline will process data from the JWST Fine Guidance Sensor (FGS) guide star acquisition process.

FGS data are generated on-board by four guide star functions associated with the guide star acquisition and tracking sequence; Identification, Acquisition, Track, and Fine Guide. The Identification function obtains an image of the sky in the FGS 2.3'x2.3' field of view and identifies the designated guide star based on its position and intensity by pattern matching the observed scene to the scene predicted by the ground system. The Acquisition function images the guide star using first an 8.8"x8.8" and then a 2.2"x2.2" window, providing the attitude control system (ACS) with the guide star's location to eliminate most of the coarse pointing error. The FGS next executes the Track function, imaging the guide star in a 2.2"x2.2" window, providing ACS with guide star centroids every 64 milliseconds in closed loop. When ACS places the guide star at the desired position on the FGS detector, the FGS transitions to the Fine Guide function, imaging the guide star in a 0.55"x0.55" window, providing guide star centroids to ACS every 64 milliseconds. Data from all four guide functions are captured to the on-board solid state recorder and downlinked with the science data.

The DMS generates Flexible Image Transport System (FITS) Guide Star Pipeline products that capture FGS data from the guide star functions and provide detailed information on spacecraft jitter. Additional inputs to the Guide Star Pipeline include Observatory Status Files, the Proposal and Planning Subsystem Database, and the DMS Engineering Database. The Identification function images the field of view by taking of a set of detector subarray "strips" that collectively cover most of the detector. The Acquisition function locates the guide star in 128x128 subarray images and then in smaller 32x32 subarray images. The Track function repositions the 32x32 subarray to keep guide star centered. During the Track function the guide star location is provided to ACS at 16 Hz. In Fine Guide the FGS flight software measures the guide star location in a fixed 8x8 subarray and provides it to ACS at 16 Hz. All FGS guide star images employ the Correlated Double Sample (CDS) image technique, except for Fine Guide, which uses Fowler-4 integration. All of the data are run through a calibration pipeline. The guide star position on the FGS detector is captured in FITS tables every 64 milliseconds for the Track and Fine Guide functions. The Fine Guide function will generate the largest data file with a typical Fine Guide data file containing approximately 200 MB of data.

Data products from the Guide Star Pipeline will be generated for each JWST visit and archived to the Mikulski Archive for Space Telescopes (MAST) along with all other JWST science data products.

9910-117, Session PWed

The JWST-MIRI MRS calibration pipeline

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The Mid-Infrared Instrument (MIRI) Medium Resolution Spectrometer (MRS) is the only mid-IR Integral Field Spectrometer on board James Webb Space Telescope. Even though the JWST pipeline will be built by the Space Telescope Science Institute, the European Consortium that developed MIRI is responsible for designing a calibration pipeline that ensures the users will have available the best quality data for their science. The complexity of MIRI, and in particular the MRS, required a very specialised pipeline with steps specific for the MRS such as fringe corrections, wavelength offsets, etc. The pipeline results and steps will be different also for point or extended source observations. On top of that, the pipeline will have two different variants: the "default", automatic pipeline, optimized for most forseen science cases, and the "advanced", more specific pipeline, where extra steps will be needed for different science cases, and expert users can interact with the structure of the pipeline. All versions of the MRS pipeline will be presented by the MRS team lead, as well as the different steps and algorithms used, structure of the input and output science data, accesory data, etc

9910-118, Session PWed

Three axis feed array correlator for the 21cm radiation detection coming from early universe

Rosario F. Cimmino, Consorzio Nazionale Interuniversitario per i Transporti e la Logistica (Italy); Francesco Romano, EExSKA (Italy); Alessandro Trifiletti, Sapienza Univ. di Roma (Italy); Antonio Saitto, Consorzio Nazionale Interuniversitario per i Transporti e la Logistica (Italy)

The SKA Radio Telescope program detects 21 cm signals which represent a probe of Early Universe.

The 21 cm radiations transfers both cosmological as well astrophysical information. Such radiation is composed by three dimensional signal components, fitting the three dimensional representation model developed by the last generation numerical simulator.

Currently, since only a bi-dimensional detection is implemented during observation, part of the signal information are lost or made unavailable for the processor.

A three-dimensional retrieval to efficiently detect all the radiation information would be useful in order to reconstruct extremely large scale as well small scale spectrum.

Such detection has to be compliant with the last generation three dimensional numerical simulator to a better interpretation of complex events.

The paper examines 21 cm radiation characteristics. Additionally, the work focuses on effective three dimensional Feed Array Correlator performances required to: perform ambiguity immunity, increase dynamic range and increase sensitivity.

The paper shows as the three dimensional Feed Array Correlator detection may be useful to optimize the complexity of the the simulators needed to interpret the observations data coming from the deep dark.

9910-119, Session PWed

Evolution of operations for the survey telescope at Paranal

Cristian M. Romero, Steffen Mieske, Andres Pino, Susana Cerda, Stéphane Brillant, European Southern Observatory (Chile)

Since 2009 began operations Surveys Telescopes at Paranal Observatory, which aim to make observations using a large field of view through which you can detect how much fainter sources also cover wide areas of sky quickly. The first to enter the telescope operations was VISTA (Visible and Infrared Survey Telescope for Astronomy) and subsequently the VST Telescope (VLT Survey Telescope). The survey telescopes were a change of the operational model adopted until then, they had the distinction of being 100% operated by an operator of telescope and instruments without the support of a support astronomer. This prompted the gradual and steady improvement of tools for the operation of the observatory within both generally and in particular these Telescopes, Examples of these enhancements include control systems for image quality, selection of Obs, logging in evening activities among others. However the new generation instruments on the Very Large Telescope (VLT) propose a new challenge to our observatory from scientific and operational point of view, as these new systems would be more demanding and complex and it would be more complicated to operate and require additional support.

That is why the focus of this study aims to explore the possible development and optimization of the operations of Surveys telescopes, which would give greater operational flexibility given the new situation looming, and to determine the feasibility of redistribution of their operators if necessary during periods of increased demand from other systems from the VLT.

9910-120, Session PWed

PHOENIX: the production line for science data products at ESO

Reinhard Hanuschik, European Southern Observatory (Germany)

In the past two years ESO has installed a production line for level 2 science data products. Focussing on spectroscopic observations, these in-house generated data products are complementary to the externally provided data products from the imaging and spectroscopic surveys. The production line combines mass production (more than one million spectra have been generated so far), previews, and quality control concepts.

9910-121, Session PWed

The ESO science data product standard for 1D spectral products

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Since 2011, ESO operates the Phase 3 process that closes the loop with the community following Phase 1 (propoosal submission) and Phase 2 (preparation and definition of the observations). Phase 3 allows the upload, validation, storage, and publication of science data products through the ESO Science Archive Facility (SAF).

Via the Phase 3 process, nearly 2 million data products have been archived and published to date; a large fraction of them, more than 80%, are one-dimensional extracted and calibrated spectra. Central to the Phase 3 process is the ESO science data product standard that defines the data format and the metadata information of any data product type.

This contribution describes the ESO science data product standard for 1d spectra, along with the operational and legacy value such standard brings to the SAF, its adoption for the routine publication of the ESO in-house generated reduced science spectra of selected spectroscopic instrument modes (currently UVES echelle, HARPS, Xshooter echelle, FLAMES-Giraffe Medusa, more to come). The usage statistics for the data access and dowload will also be provided, highlighting the legacy value of the ESO spectroscopic public surveys (PESSTO, GAIA-ESO) and of the ESO large programmes.

9910-122, Session PWed

Building a pipeline of talent for operating radio observatories

Lory M. Wingate, National Radio Astronomy Observatory (United States)

In the U.S., as around the world, there is a strong desire to develop further our human capacity in the Science, Technology, Engineering, and Mathematics (STEM) fields, especially within traditionally under-represented groups. Within the mandate and mission statement of NRAO we define under-represented groups to mean all of the following but not limited to people of color, women, economically disadvantaged and first-generation college students.

The National and International Non-Traditional Exchange Program (NINE) is part of the NRAO Office of Diversity and Inclusion. It is geared towards increasing under-represented participation in STEM fields associated with radio astronomy through enticing the best and brightest, both nationally and internationally, into high quality programs designed to benefit the participant, each partnering location, and the radio astronomy community as a whole.

The NINE's primary objectives are to 1) provide supported short programs (up to three month's duration) designed to teach sustainable skills in any STEM functional area associated with radio astronomy that can ultimately be applied in the home location, 2) to form long-term mentor/mentee relationships with staff at NRAO, and 3) position the participant to successfully develop a NINE Hub, capable of providing training in the STEM field of experience at their home location.

The Program provides learning opportunities throughout all disciplines affecting the full spectrum of activities associated with designing, constructing, and operating, radio astronomy observatories (Human Resources, Education and Public Outreach, Electronics, Engineering, Technicians, Operators, Project Management, Systems Engineering, and many others). The anticipated outcome of this program is worldwide partnerships with fast growing radio astronomy communities designed to facilitate the exchange of faculty and the co-mentoring of under-represented groups of students, thereby developing a strong pipeline of global radio astronomy talent.

Specifically, the NINE Program consists of process learning, hands-on experience, mentoring/teaching techniques, NINE Hub Program development, and NINE Hub Program exchanges. Process learning includes preparing for and completing an international standard processes certification used to achieving successful project outcomes and optimize science results. Hands-on learning includes learning associated with radio astronomy during construction of radio equipment, testing, commissioning, and observations. Mentoring/teaching includes learning the basics on how to instruct and mentor other participants, and understanding how to provide training events to be provided at the home site. NINE Hub Program development includes the identification and securing of tools, physical space, and processes needed at the home location. And the NINE Hub Program exchanges include developing the processes to identify potential students and postdocs, faculty/instructors and other professionals and facilitating their engagement in the NINE Program.

Participation in the NINE Program is through a competitive process. Participants are selected by a panel that assesses fitness for the Program through application review, discussions with references, and mentor and budget availability.

This presentation describes the Program and its elements, as well as the lessons learned in implementing the program in the international environment.

9910-123, Session PWed

Training telescope operators and support astronomers at Paranal

Henri M. J. Boffin, European Southern Observatory (Germany); Dimitri A. Gadotti, Joe Anderson, Andres Pino, Julien H. V. Girard, Willem-Jan de Wit, European Southern Observatory (Chile)

The operations model of the ESO Paranal Observatory relies on the work of efficient telescope and instrument operators as well as astronomers to carry out all the day- and night-time tasks. This is highly dependent on adequate training of the staff. The Science Operations department of the ESO Paranal Observatory (SciOps) has a training group that devises a well-defined and continuously evolving, training plan for new staff, in addition to broadening and reinforcement courses for the whole department. This paper presents the training activities for and by SciOps, including recent astronomical and quality control training for operators, as well as adaptive optics and interferometry training of all staff.

9910-124, Session PWed

Characterizing silicon pore optics stacks

Giuseppe Vacanti, Nicolas M. Barrière, Abdelhakim Chatbi, cosine Science & Computing B.V. (Netherlands); Max Collon, cosine B.V. (Netherlands); Ramses Günther, Roy van der Hoeven, Boris Landgraf, Mark Vervest, Alex Yanson, cosine Science & Computing B.V. (Netherlands); Marcos Bavdaz, Eric Wille, European Space Agency (Netherlands)

In this paper we describe how the data obtained at the XPBF is processed in an automatic fashion to generate a large number of diagnostic and characterization data results. The pipeline can be run live, during the measurement, so that within a few minutes of a measurement being completed a complete X-ray characterizaion is available for immediate feedback.

9910-126, Session PWed

A schedule optimizer for astronomical observations under constraints

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Telescope time is precious; the scheduling of observations must be as efficient as possible in terms of time usage and obtained data quality. The optimization of the schedules of observations, which include hundreds of targets to be observed in different runs, with sometimes tricky and/or time-dependant constraints cannot be done manually. In addition, this optimization must be fast for real-time use. This is the case, for instance, for big surveys spanning several years to search for extrasolar planets, which rely on the use of Angular Differential Mode (ADI).

In this context, we have developed a software (SPOT) that can compute long term (months, years) and short term (night) optimized schedules of such surveys, taking into account constraints that include all classical astronomical constraints plus specific constraints related to ADI observations. SPOT is now routinely used to schedule GTO SPHERE observations on the VLT. It is also used to determine the best observing dates given a list of targets, or, alternatively, to optimize a list of targets, once the dates of observations are known.

We are now investigating possible coupling i/ with weather forecast for short term response to atmospheric conditions and ii/ with long term meteorological data to improve the target list preparation.

SPOT could be easily used for queue-scheduling, or could be extended to integrate new and more complex types of constraints.

9910-35, Session 8

Getting NuSTAR on target: predicting mast motion

Karl Forster, Kristin K. Madsen, Hiromasa Miyasaka, California Institute of Technology (United States); William W. Craig, Space Sciences Lab. (United States); Fiona A. Harrison, Vikram R. Rana, California Institute of Technology (United States); Craig B. Markwardt, NASA

Goddard Space Flight Ctr. (United States)

The Nuclear Spectroscopic Telescope Array (NuSTAR) is the first focussing high energy (3-79 keV) X-ray observatory operating for four years from low Earth orbit. The X-ray detector arrays are located on the spacecraft bus with the optics modules mounted on a flexible mast of 10.14m length. The motion of the telescope optical axis on the detectors during each observation is measured by a laser metrology system and matches the pre-launch predictions of the thermal flexing of the mast as the spacecraft enters and exits the Earths shadow each orbit. However, an additional motion of the telescope field of view was discovered during observatory commissioning that is associated with the spacecraft attitude control system and an additional flexing of the mast correlated with the Solar aspect angle for the observation. We present the methodology developed to predict where any particular target coordinate will fall on the NuSTAR detectors based on the Solar aspect angle at the scheduled time of an observation. This may be applicable to future observatories that employ optics deployed on extendable masts. The automation of the prediction system has greatly improved observatory operations efficiency and the reliability of observation planning.

9910-36, Session 8

Oprimizing GESE operations by orbit selection and system design

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Operation of a small survey telescope in space is markedly simpler than operations of ground-based telescopes driven by user selection or transient events. Nevertheless, both types of telescopes share two common challenges: maximizing the integration time on target, while minimizing operation costs including communication costs and staffing on the ground. We use the example of the Galaxy Evolution Spectroscopic Explorer (GESE) to show how these challenges can be met through a custom orbit and a system design emphasizing simplification and leveraging information from ground-based telescopes.

9910-37, Session 8

Feature-based telescope scheduler

Elahesadat Naghib, Robert J. Vanderbei, Princeton Univ. (United States); Christopher W. Stubbs, Harvard Univ. (United States)

In the era of expensive astronomical instruments, efficient scheduling of their operation is receiving increasing attention. For a telescope similar to the Large Synoptic Survey Telescope (LSST) with operating costs of approximately $40M/year, a mis-scheduling of only 5% (around 50 visits a night) would be equivalent to a loss of 20 million dollars over a decade of operation. Thus, an appropriate maximization of the number of visits seems to be necessary. Moreover, not only the number of observations is important, but also the cadence of observations, airmass distribution, and depth will characterize the performance of the telescope. The challenge is to devise a scheduling algorithm that maximizes the scientific return of the system, given a complex set of constraints and scientific merit that includes sky coverage, co-added depth, and sampling in the time domain across the survey filters.

This study proposes an efficient scheduler that consists of a fast (sub-linear) online controller, and an offline supervisory control-optimizer. The online control law is computed at the moment of decision for the next visit, t, and has a much faster response than the timescale of changes in operational conditions such as the weather, visibility, and sky brightness. Accordingly, these inherently unpredictable variables can in fact be considered as deterministic inputs for the controller at t. This feature eliminates concerns about the sub-optimality caused by probabilistic representation of the above-mentioned disturbances in the decision process. The offline control optimizer is designed to carry most of the computational burden, and accordingly time consumption of the scheduler. Although the efficiency of the supervisory system is not as critical as that of the online controller, in order to reduce the cost of implementation, a variant of Differential Evolution (specially designed for this scheduler) is used which is particularly conducive to parallel computation. The supervisory optimizer trains the controller using a telescope simulator by maximizing a performance function. In this procedure, the controller is exposed to different possible environments and observation histories to learn the optimal response to different real-time scenarios. The performance function is computable at the end of the simulated observations and accounts for all scientific/engineering constrains, as well as the high-level, long-term mission objectives (such as almost uniform coverage of the sky for the case of LSST). Moreover, any constraint or preference can be easily added or removed at any time which makes the scheduler flexible to changes in the scientific metrics or mission objectives. This approach is also capable of feedback-based self-adjustments.

In order to produce a tractable problem for the offline optimization, a reduced approximate state-space called feature-space is also introduced in this study. Preliminary results for a model of LSST, implemented in Python 2.7, is promising in terms of both optimality (100 visits per hour), and the computational cost (8.5 hours for optimizing the controller over an average night using a 2.7 GHz Intel Core i5 CPU with 8 GB 1333MHz memory).

9910-38, Session 8

Ongoing evolution of proposal reviews in the Spitzer warm mission

Lisa J. Storrie-Lombardi, Nancy Silbermann, Luisa M. Rebull, John R. Stauffer, Megan Crane, Seppo Laine, Lee Armus, Spitzer Science Ctr. (United States) and California Institute of Technology (United States); Suzanne R. Dodd, Jet Propulsion Lab. (United States)

The Spitzer Space Telescope is executing the seventh year of extended warm mission science. From launch in 2003, Spitzer cryogenic mission operations lasted until May of 2009 when the cryogen was depleted. Warm operations have continued since July 2009 using the 3.6 and 4.5 micron channels of the IRAC instrument. The observatory still executes 7000 hour of science per year but the size of the operations staffing has been reduced by 70%.

During the cryogenic mission the proposal reviews were week-long, in-person meetings of 80-100 scientists that met in topical science panels followed by a time allocation committee to review and discuss the proposals. When warm operations began we introduced panel reviews via telecon. The panels recommended the awards for the smaller proposals. This was followed later by an in-person time allocation committee meeting to recommend awards for the larger proposals. Introducing the telecon panel reviews reduced the cost of the annual process substantially as only 10-15% of the reviewers need to travel to the time allocation committee meeting.

In 2014 the process for the solicitation and selection was further compressed due to changes in the mission funding profile, leading to another change in the review process for the smaller proposals. The large proposals are still reviewed by a time allocation committee that meets in person to discuss and review the proposals but the smaller proposals are no longer discussed by a topical science panel. For the 2014 cycle we solicited a larger pool of reviewers who are guaranteed they will receive no more than 20 proposals that they read, grade, rank, and provide comments for, and that completes their service. The advantages are that proposals can be better targeted to expert reviewers because there are no issues with potential conflicts with other panel members. It is also substantially easier to get reviewers to say yes to a process with a small number of proposals to read and no travel or telecon commitment. The disadvantages are that disparate opinions from the reviewers are not resolved in a panel discussion. The SSC does the merge of the grades and comments to create the final ranked list of proposals.

This new process has been utilized for two observing cycles and we discuss here our experience with it so far and the pros and cons of this methodology.

9910-109, Session 8

Sharing the skies: the Gemini Observatory international time allocation process

Steven J. Margheim, Gemini Observatory (United States)

Gemini Observatory serves a diverse community of four partner countries (United States, Canada, Brazil, and Argentina), two hosts (Chile and University of Hawaii), and limited-term partnerships (currently Australia and the Republic of Korea). Observing time is available via multiple opportunities including Large and Long Programs, Fast-turnaround programs, and regular semester queue programs. The primary factors that inform the overall schedule of observing programs are a desire to allocate the available observing time in proportion to a partner's financial contribution (partner share), and to reach target completion rates as set by the Gemini Board. The slate of programs for observation each semester must be created by merging programs from these multiple, conflicting sources. This paper describes the time allocation process used to schedule the overall science program for the semester, with emphasis on the International Time Allocation Committee and the software applications used.

Each partner (or host) has an independent peer-review process to assess their community's proposals. The outcome of these National Time Allocation Committees (NTACs) are ranked lists of approved programs and the desired partner's time allocation. These are forwarded to the observatory for consideration by the International Time Allocation Committee (ITAC). The ITAC is composed of a representative from each partner (or host) country and led by a member of the observatory's scientific staff, the ITAC Chair.

The ITAC Chair merges the programs forwarded by each NTAC to produce a draft queue. The merging process primarily involves stepping through each partner's ranked programs and distributing the time in proportion to each partner's share; while also ensuring that any particular observing constraint, such as Right Ascension or Cloud Cover, is not over-subscribed. This process is primarily accomplished through the use of a custom software package, the "ITAC Software", detailed in this paper.

Draft queues are shared with the ITAC members and the Heads of Science Operations, who construct the semester telescope schedule in parallel. This draft queue is analyzed for many factors including instrument availability, duplication of observations, and the distribution of targets and observing constraint requests. The ITAC chair incorporates feedback from each draft queue and additional iterations are completed until the ensemble of proposals approaches the optimal queue, for both the partners and observatory. Typically, this process occurs over a 2-3 week period, and involved 6-10 major iterations within the ITAC. Once the members of the ITAC have agreed upon a proposal slate of programs, it is forwarded to the Gemini Director for approval.

9910-39, Session 9

The LSST Scheduler from design to construction

Francisco Delgado, LSST (United States)

The Large Synoptic Survey Telescope (LSST) will be a highly robotic facility, demanding a very high efficiency during its operation. To achieve this, the LSST Scheduler has been envisioned as an autonomous software component from the Observatory Control System (OCS) that drives the survey selecting the sequence of targets in real time by optimizing a dynamic cost function of more than 200 parameters. Multiple science programs produce thousands of candidate targets for each visit, and multiple telemetry measurements are received to evaluate the external and the internal conditions of the observatory. The design of the LSST Scheduler started early in the project supported by Model Based Systems Engineering, detailed prototyping and scientific validation of the survey capabilities required. In order to build such a critical component, an agile development path in incremental releases is presented, integrated to the development plan of the Operations Simulator (OpSim) to allow constant testing, integration and validation in a simulated OCS environment. The final product is a Scheduler that is also capable of running 2000 times faster than real time in simulation mode for survey studies and scientific validation during commissioning and operations.

9910-40, Session 9

Determining the direct and indirect impact of commercial aircraft on LSST observing efficiency

Rose K. Gibson, Wellesley College (United States); Chuck Claver, LSST (United States); Christopher W. Stubbs, Harvard Univ. (United States); Michael Warner, Cerro Tololo Inter-American Observatory (Chile)

The Large Synoptic Survey Telescope (LSST) is a ten-year survey that will map the southern sky in six different filters 800 times before the end of its run. We explore the primary effect of airline traffic on scheduling the LSST observations in addition to the secondary effect of condensation trails, or contrails, created by the presence of the aircraft. The large national investment being made in LSST implies that small improvements in observing efficiency through aircraft and contrail avoidance can result in a significant improvement in the quality of the survey and its science. A Software Defined Radio (SDR) received Automatic Dependent Surveillance-Broadcast (ADS-B) signals from commercial aircraft in order to monitor and record plane activity over the LSST site. We installed an ADS-B ground station on Cerro Pachón, Chile consisting of a 1090Mhz antenna on the Andes Lidar Observatory feeding a RTL2832U SDR. The Python software dump1090 converted the ADS-B telemetry into Basestation format, and we found that even during the busiest time of the night there were only 4 signals being received each minute on average, which will have very small direct effect, if any, on the LSST observing scheduler. We are also able to use the the ADS-B data in combination with a correlation between a glitch on 3 channels of the LSST sky-brightness sensor with aircraft beacons to avoid pointing LSST towards contrails, reducing the systematic error in photometry during otherwise photometric conditions.

9910-41, Session 9

Survey strategy optimization for the Atacama Cosmology Telescope

Francesco De Bernardis - for the ACT collaboration, Cornell Univ. (United States)

In recent years there have been significant improvements in the sensitivity and the angular resolution of the instruments dedicated to the observation of the Cosmic Microwave Background (CMB). ACTPol is the first polarization receiver for the Atacama Cosmology Telescope (ACT) that is observing the CMB sky with arcmin resolution over ~ 2000 sq. deg. Its upgrade, Advanced ACTPol, will observe the CMB in five frequency bands and over a larger area of the sky. We describe the optimization and implementation of the ACTPol and Advanced ACTPol surveys. The

selection of the observed fields is driven mainly by the science goals, that is, small angular scales CMB measurements and cross-correlation studies. For the ACTPol survey we have observed patches of the southern galactic sky with low galactic foregrounds emission while maximizing the overlap with several galaxy surveys to allow unique cross-correlation studies. A wider and less deep field in the northern galactic cap ensures significant additional overlap with the BOSS spectroscopic survey. The exact shapes and footprints of the fields are optimized to achieve uniform coverage and to obtain cross-linked maps by observing the fields at orthogonal scan directions. We have maximized the efficiency of the survey by implementing a close to 24 hour observing strategy, switching between a daytime and a nighttime observing plan and minimizing the telescope idle time. We describe the challenges represented by the survey optimization for the significantly wider area observed by Advanced ACTPol and the software package used to optimize and implement the ACT surveys.

9910-42, Session 9

SNR-based queue observations at CFHT

Daniel Devost, William Mahoney, Claire Moutou, Canada-France-Hawaii Telescope (United States)

The Canada-France-Hawaii Telescope has been observing in Queued Service Observing (QSO) mode since 2000. The QSO system has proven to be quite efficient compared to classical observing since CFHT is now routinely complete more than 75 percent of its high priority science programs. In an effort to optimize the night time utilizing the exquisite weather on Maunakea, CFHT is now moving it's QSO based observations toward Signal to Noise (SNR) observing. In this new mode, individual exposure times for a science program are determined using an estimate of the seeing conditions. The science program is considered completed when the depth required by the scientific requirements is reached. This way, the good seeing conditions on Maunakea are used more effectively, allowing for the completion of more programs. I will review the concept of SNR observations and show how the concept is implemented with CFHT's instruments.

9910-44, Session 9

Pandeia: a multi-mission exposure time calculator for JWST and WFIRST

Klaus M. Pontoppidan, Timothy E. Pickering, Victoria G. Laidler, Karoline Gilbert, Christopher D. Sontag, Christine Slocum, Mark J. Sienkiewicz Jr., Christopher Hanley, Nicholas M. Earl, Laurent Pueyo, Swara Ravindranath, Diane M. Karakla, Massimo Robberto, Alberto Noriega-Crespo, Elizabeth Barker, Space Telescope Science Institute (United States)

Exposure time calculators (ETCs) are integral parts of any large observatory. They are often one of the first places new users go to explore and familiarize themselves with the capabilities of a new facility, and one of the last tools that are used before submitting an observing program for evaluation by a time allocation committee. As such, there is a strong drive to develop ETCs that accurately model a telescope/instrument combination, as well as provide the user with an intuitive, easy-to-use, yet powerful interface. The JWST ETC system -- Pandeia -- is the environment in which a user will explore an observing concept, before deciding to write a proposal, and then craft specific observation sequences.

During the JWST era, users will benefit from features that go well beyond what has previously been offered as part of an exposure time calculator. Such features include algorithms that closely model data's acquisition, structure, and post-processing; advanced, interactive graphical user interfaces (GUIs), more powerful tools to visualize a large parameter volume, and functionality to share work efficiently. The JWST ETC is required to support instrument modes that generate large amounts of information, including integral field unit (IFU) spectroscopy and multi-object spectroscopy with the NIRSpec Multi-Shutter Array (MSA). Calculations must be accurate for modern observational modes that depend on high signal-to-noise and high contrast data, including exoplanet spectroscopy, coronagraphy and non-redundant aperture masking.

A common property of JWST observations is that they are recorded as sets of two-dimensional detector exposures; all information is at some point stored in discrete detector pixels. Different observing modes fundamentally differ in two aspects: First, how light is projected and/or dispersed onto a detector and second, how observational products are extracted from a set of exposures, typically by a linear combination of pixel values. The ETC generalizes both of these steps by adopting a three-dimensional, pixel-based approach. The user can create complex astrophysical scenes consisting of multiple sources with different spectral and spatial properties. By modeling individual detector pixels the ETC can explicitly mimic many of the steps taken in the calibration and reduction of actual JWST data, leading to more accurate results that are easier to test and interpret. To facilitate extensive forward-model parameter explorations, the ETC engine is optimized for calculations of small "postage-stamp" regions on angular scales of a few arcseconds. This approach can generally lead to processing times as fast as a few seconds per calculation, depending on observing mode.

Key features of the Pandeia ETC include: Full support of a wide variety of imaging, coronagraphic and spectroscopic instrument modes, MULTIACCUM readout modes, correlated noise, advanced astronomical scene creation, an interface to the JWST background model, fully data-driven with verified reference data, including throughputs, point spread functions and detector properties, and extensible and modular Python engine. While developed for JWST, Pandeia is currently also extended for use with the WFIRST imager and IFU instruments as they are currently prototyped.

9910-45, Session 9

Proposal creation, submission, and evaluation: the OPAL example

Jill Rathborne, Jessica Chapman, Phillip G. Edwards, Arkadi Kosmynin, Douglas C. Bock, CSIRO Astronomy and Space Science (Australia)

The Australia Telescope National Facility (ATNF) operates a suite of radio telescopes in Australia and receives ~350 proposals per year from the international scientific community eager to use these telescopes. Since 2006 OPAL, the Online Proposal Applications and Links, has been used to handle all proposals received by the ATNF. OPAL is a web-based application that provides a set of tools that allow users to (1) create, modify, save, submit, update and withdraw proposals during an application period, (2) access their own current and previous proposals, and (3) see grades and comments provided by ATNF's Time Assignment Committee (TAC). OPAL also provide a critical link to our data archives. In addition, OPAL also provides tools for the TAC and telescope scheduler that are integral to the proposal review and time allocation process. In this talk I will provide an overview of OPAL's capabilities, highlight its key features, and showcase its versatility from the perspective of both users and support staff.

9910-46, Session 9

Hinode/EIS science planning and operations tools

Jonn A. Rainnie, STFC Rutherford Appleton Lab. (United Kingdom)

We present the design, implementation and maintenance of the suite of software enabling scientists to design and schedule Hinode/EIS operations. The total of this software is the EIS Science Planning Tools (EISPT), and is predominately written in IDL (Interactive Data Language), coupled with SolarSoft (SSW), an IDL library developed for solar missions.

Hinode is a multi-instrument and wavelength mission designed to observe the Sun. It is a joint Japan/UK/US consortium (with ESA and Norwegian involvement). Launched in September 2006, its principal scientific goals are to study the Sun's variability and the causes of solar activity.

Hinode operations are coordinated at ISAS (Tokyo, Japan). A daily Science Operations meeting is attended by the instrument teams and the spacecraft team. Nominally, science plan uploads cover periods of two or three days. When the forthcoming operations have been agreed, the necessary spacecraft operations parameters are created. These include scheduling for spacecraft pointing and ground stations.

The Extreme UV Imaging Spectrometer (EIS) instrument, led by the UK (the PI institute is MSSL), is designed to observe the emission spectral lines of the solar atmosphere.

Observations are composed of reusable, hierarchical components, including lines lists (wavelengths of spectral lines), rasters (exposure times, line list, etc.) and studies (defines one or more rasters).

Studies are the basic unit of 'timeline' scheduling. They are a useful construct for generating more complex sequences of observations, reducing the planning burden. Instrument observations must first be validated.

An initial requirement was that operations be shared equally by the 3 main EIS teams (Japan, UK and US). Hence, a major design focus of the software was 'Remote Operations', whereby any scientist in any location can run the software, schedule a science plan and send it to the spacecraft commanding team. It would then be validated and combined with the science plans of the other instruments. Then uploaded to the spacecraft.

As for any space mission, telemetry size and rate are important constraints. For each planning cycle the instruments are issued a maximum data allocation. EISPT interactively calculates the telemetry requirements of each observation and plan.

Autonomous operations was a challenging concept designed to observe the early onset of various dynamic events, including solar flares. The planning cycle precluded observers responding to such short-term events.

Hence, the instrument can be run in a (low-telemetry) 'hunter' mode at a suitable target. Upon detecting an event the current observation ceases and another automatically begins at the event location. This 'response' observation involves a smaller field-of-view and higher cadence. It's impossible to predict if this mechanism will be activated, and if so how much telemetry is acquired.

The EISPT has operated successfully since it was deployed in November 2006. Nominally it is used six days a week. It has been maintained and updated as required to take account of changing mission operations. A large update was made in 2013/14 to develop the facility to coordinate observations with other solar missions (SDO/AIA and IRIS).

9910-48, Session 9

An optical to IR sky brightness model for the LSST

Peter Yoachim, Univ. of Washington (United States); Michael Coughlin, Harvard Univ. (United States); George Z. Angeli, Chuck Claver, LSST (United States); Andrew J. Connolly, Univ. of Washington (United States); Kem H. Cook, Cook Astronomical Consulting (United States); Scott Daniel, Zeljko Ivezic, R. Lynne Jones, Univ. of Washington (United States); Catherine E. Petry, LSST (United States); Michael A. Reuter, LSST (United States); Christopher W. Stubbs, Harvard Univ. (United States); Bo Xin, LSST (United States)

To efficiently survey the night sky requires a detailed knowledge of the sky brightness and how it evolves as a function of time, position of the moon, and solar activity. To develop this knowledge the Large Synoptic Survey Telescope (LSST), as part of its simulations program, has developed an open-source python code to calculate the expected night sky emission on Cerro Pachon. This code uses the ESO SkyCalc Sky Model Calculator (Noll et al. 2012; Jones et al. 2013) to generate a suite of 3,500 template spectra that can be interpolated to arbitrary observing conditions. These template spectra include components for scattered moonlight, zodiacal light, airglow, scattered starlight, and upper and lower atmosphere emission. To determine how far into twilight the LSST can observe (in the z and y filters) we have extended the sky model to predict twilight sky conditions. This model is an analytic fit to observations made with a Canon all-sky camera located at the LSST site. These observations have been run through a photometry pipeline to generate a database with 91.5 million measurements of the sky brightness spanning a range of 311 days. From these data we find that, for sun altitudes between -11 and -20 degrees and airmasses less than 2.5, the twilight component of the sky can be fit with a model with only 4 free parameters. Early validation of the LSST sky model shows that dark-time zenith predictions match the observations with an RMS of 0.2 magnitudes. We attribute most of this variation to random variations in the weather, as the residuals show no significant trend with time of night or time of year.

9910-49, Session 9

Measurements of airglow at Gemini Observatory on Maunakea in the optical and infrared

Adam Smith, Katherine C. Roth, Andrew Stephens, Olesja Smirnova, Gemini Observatory (United States)

Gemini Observatory on Mauna Kea has been collecting optical and infrared science data for almost 15 years. We have analyzed imaging data from two of the original facility instruments, GMOS and NIRI, in order to measure sky brightness levels in multiple infrared and optical broad-band filters. We present measured background levels as a function of several operational quantities (e.g. moon-phase, hours after/before twilight, seasons). We find that airglow is a significant contributor to background levels in several filters. Gemini is primarily a queue scheduled telescope, with observations being optimally executed in order to provide the most efficient use of telescope time. However, without any means to schedule observations as a function of airglow we find that some imaging observations may not be meeting the expected sensitivity requirements. We suggest that in order to improve the delivered queue data quality an airglow monitor could be adopted and airglow brightness be incorporated into the Integration Time Calculator as part of the sky background quantity used to schedule observations.

9910-50, Session 10

Two years of LCOGT network operations: the challenges of a global observatory

Nikolaus Volgenau, Las Cumbres Observatory Global Telescope Network (United States)

With 18 telescopes distributed over 6 sites, and more telescopes being added in 2016, Las Cumbres Observatory Global Telescope Network is a unique resource for time-domain astronomy. The Network began providing observations for members of its Science Collaboration and other partners in May 2014. In the two years since then, LCOGT has made a number of improvements to increase the Network's science yield. We also now have two years' experience monitoring observatory performance; effective

monitoring of an observatory that spans the globe is a complex enterprise. This presentation describes LCOGT's efforts to monitor site conditions, instrument performance, the quality of science data, and the efficiency of the scheduling software.

The Network's continuous coverage of the night sky, and the optimization of the observing schedule over all sites simultaneously, have enabled LCOGT-users to produce significant science results. However, practical challenges to maximizing the Network's science output remain. Overcoming some of these challenges will require increasing the sophistication of our Network scheduling. Some examples are the following: Long-duration observations, which can benefit studies of exoplanet transits, microlensing events, and lensed quasar time delays, should be automatically passed from one site to another. Requests to observe in multiple filters simultaneously should be linked, so that either all observations are attempted or rejected (and so can be rescheduled at another site). And requests for immediate (target-of-opportunity) observations, which are critical for GRB and SN-progenitor investigations, should be acted on as quickly as possible but be otherwise minimally disruptive.

Weighing the priorities of observing requests for large and small projects is a thorny issue. On the one hand, thousands of hours have been allocated to LCOGT's (high priority) key projects, dedicated to exoplanet microlensing (PI: R. Street), supernova characterization (PI: D. Howell), and AGN reverberation mapping (PI: K. Horne). But on the other hand, some key project data are more important than others, and smaller projects that request a few hours to observe a few events shouldn't repeatedly be squeezed out of the schedule.

In 2015, new Sinistro cameras, which were designed and built in-house, replaced commercial SBIG cameras on the Network's 1-meter telescopes. The need to develop the necessary site infrastructure and install the Sinistros had to be balanced against the need to keep sufficient telescopes available for science observations. LCOGT is facing this challenge again with future instrument upgrades, including the 2016 deployment of the Network of Robotic Echelle Spectrographs (NRES, see contribution by Siverd).

9910-51, Session 10

Dark energy survey operations: years 1 to 3

H. Thomas Diehl, Fermi National Accelerator Lab. (United States)

The Dark Energy Survey (DES) is a next generation optical survey aimed at understanding the accelerating expansion of the universe using four complementary methods: weak gravitational lensing, galaxy cluster counts, baryon acoustic oscillations, and Type Ia supernovae. To perform the 5000 sq-degree wide field and 30 sq-degree supernova surveys, the DES Collaboration built the Dark Energy Camera (DECam), a 3 square degree, 570 Megapixel CCD camera that was installed at the prime focus of the Blanco 4-meter telescope at the Cerro Tololo Inter-American Observatory in 2012. A DES season comprises 105 nights of observations from August to mid February. DES "Year 1" (of 5) was 2013 to 2014. We will finish "Year 3" in February 2016. This presentation will describe DES, the strategy and goals for the first three season's data, the performance of the camera, and the efficiency of survey operations.

9910-52, Session 10

Lessons from and methods for surveying large areas with the Hubble Space Telescope

John W. MacKenty, Space Telescope Science Institute (United States)

Although the imagers on the Hubble Space Telescope only provide fields of view of a few square arc minutes, the telescope has been extensively used to conduct large surveys. These range of relatively shallow mappings in a single filter, multi-filter and multi-epoch surveys, and a series of increasingly deep exposures in several carefully selected fields. HST has also conducted extensive "parallel" surveys either coordinated with a prime instrument (typically using two cameras together) or as "pure" parallel observations to capture images of areas on the sky selected by another science programs(typically spectroscopic observations). We compare various strategies and outcomes from these pure parallel observations. Recently, we have tested an approach permitting much faster mapping with the WFC3/IR detector under GYRO pointing control and avoiding the overhead associated with multiple target observations. This results in a four to eight fold increase in mapping speed (ad the expense of shallower exposures). This approach enables 250 second exposures (reaching H~25th magnitude) covering one square degree in 100 orbits.

9910-53, Session 10

Development of the Arizona Robotic Telescope Network

Benjamin Weiner, Dennis Zaritsky, The Univ. of Arizona (United States); Pavel Gabor, Vatican Observatory Research Group (United States); Nathan Smith, Scott Swindell, Chris Johnson, The Univ. of Arizona (United States); Petr Kubánek, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Victor Gasho, Buell T. Jannuzi, The Univ. of Arizona (United States)

The Arizona Robotic Telescope Network project is a long term effort to develop a system of telescopes that can carry out a flexible program of PI observing, survey projects, synoptic observing, and time domain astrophysics including monitoring, rapid response, followup and characterization of transients and targets of opportunity. Steward Observatory operates and shares in several 1-3m class telescopes with quality sites and instrumentation, largely operated in classical modes. Science programs suited to these telescopes become limited by scheduling flexibility and people-power of available observers. Our goal is to adapt these facilities for multiple co-existing queued programs, interrupt capability, remote/robotic operation, and delivery of reduced data. In the long term, planning for the LSST era, we envision an automated system coordinating across multiple telescopes and sites, where alerts can trigger followup on one telescope + instrument, automated characterization, and triggering of further observations if required, such as followup imaging that automatically triggers spectroscopy when criteria are met. We are updating telescope control systems and software to implement this system in stages, beginning with the Kuiper 61" and the Vatican Observatory's 1.8m telescopes. We present science requirements for the telescope network and the technical requirements derived therefrom, and discuss issues adopting legacy facilities, scheduling, data pipelines, and maintaining capabilities for a diverse user base.

9910-54, Session 10

Spectral calibration for the Maunakea Spectroscopic Explorer: challenges and solutions

Nicolas Flagey, Alan W. McConnachie, Richard Murowinski, Kei Szeto, Canada-France-Hawaii Telescope (United States); Shan B. Mignot, Observatoire de Paris à Meudon (France)

The Maunakea Spectroscopic Explorer (MSE) will each year obtain millions of spectra in the optical to near-infrared, at low (R~2,500) to very high (R~40,000) spectral resolution by obtaining ~3000 spectra per pointing via a highly multiplexed fiber-fed system. Key science programs for MSE include black hole reverberation mapping, stellar population analysis of faint galaxies at high redshift, and sub-km/s velocity accuracy for stellar astrophysics. This requires highly precise, repeatable and stable spectral calibration over long timescales. To meet these demanding science goals and to allow MSE to deliver data of very high quality to the broad community of astronomers involved in the project, a comprehensive and efficient calibration strategy is being developed. In this paper, we present the different challenges we face to properly calibrate the MSE spectra and the solutions we are considering to address these challenges.

9910-55, Session 10

Calibration development strategies for the Daniel K. Inouye Solar Telescope (DKIST) data center

Fraser Watson, Kevin Reardon, Steven J. Berukoff, Daniel Speiss, Scott Wiant, Tony Hays, National Solar Observatory (United States)

As telescopes have grown larger and data rates have increased, so have the challenges in providing reliable and accurate calibration strategies for transforming raw data into useful science-ready outputs. The Daniel K. Inouye Solar Telescope (DKIST), currently under construction on Haleakal?, in Maui Hawai`i will be the largest solar telescope in the world and will use adaptive optics to provide the highest resolution view of the Sun. Its data acquisition rates will be in the hundreds of thousands of frames per day, and it will deliver an average of 12TB of raw solar data on a daily basis. It is expected that DKIST data will enable significant and transformative discoveries that will dramatically increase our understanding of the Sun and its effects on the Sun-Earth environment. As a result of this, it is a priority of the DKIST Data Center team at the National Solar Observatory (NSO) to be able to deliver timely and accurately calibrated data to the astronomical community for further analysis.

The first light suite consists of five unique instruments, which are all expected to begin operations within a short window at the start of operations. These instruments are designed to work in parallel, taking simultaneous observations of a single part of the Sun in multiple wavelengths and with multiple observational schemes at the same time. As such, the calibration development effort for each instrument will involve efforts from the NSO Data Center team, the instrument developers, and the broader community. This allows us to leverage the similarities between some instruments, identify calibration processes that are common among instruments, and make use of the accumulated domain knowledge. By modularizing these steps, we will be able to increase the efficiency and effectiveness of our calibration strategy.

The facility will execute a variety of investigator-driven observing programs, which will produce day-to-day variations in the types of acquired data. In combination with large data rates and limited personnel, this will require some degree of automation to be incorporated into the calibration workflows to facilitate the generation of scientifically useful data. The heterogeneity of the data and the unpredictable variations in the seeing conditions (on timescales of seconds or minutes) introduce complexity, which requires a self-adapting, extensible calibration pipeline. In addition, our knowledge of the instrument performance and telescope characteristics will grow rapidly as the telescope begins operations, and continuously through the facility lifetime. So the automated calibration pipelines will need to be capable of modification and improvement to incorporate the new information about the DKIST system, as well as potential improvements provided by the DKIST user community.

This paper will detail the current calibration processing development strategies being used by the Data Center team at the National Solar Observatory to manage this calibration effort, so that we can deliver timely and accurately calibrated data to the DKIST user community, with as much scientific value as possible.

9910-56, Session 10

ALMA quality assurance: concepts, procedures, and tools

A. Maurizio Chavan, European Southern Observatory (Germany); Stephane L. Tanne, ALMA (Chile); Eiji Akiyama, National Astronomical Observatory of Japan (Japan); Robert Kurowski, Suzanna Randall, European Southern Observatory (Germany); Baltasar Vila Vilaro, ALMA (Chile); Eric Villard, Joint ALMA Observatory (Chile)

Data produced by ALMA for the community undergoes a rigorous quality assurance process, from the initial observation (“QA0”) to the final science-ready data products (“QA2”), to the QA feedback given by the PIs when they receive the data products (“QA3”). Calibration data is analyzed to measure the performance of the observatory and predict the trend of its evolution (“QA1”).

The procedure develops over different steps and involves several actors across all ALMA locations; it is made possible by the support given by dedicated software tools and a complex database of science data, meta-data and operational parameters. The life-cycle of each involved entity is well-defined, and it prevents for instance that “bad” data (that is, data not meeting the minimum quality standards) is ever processed by the ALMA pipeline.

9910-58, Session 10

Data mining spacecraft telemetry: towards generic solutions for automatic health monitoring and status characterization

Pierre Royer, Joris De Ridder, Bart Vandenbussche, Sara Regibo, Rik Huygen, Wim De Meester, KU Leuven (Belgium); David J. Evans, Jose Martinez, European Space Agency (Germany)

Context: As the number of spacecraft telemetry parameters and telecommands keeps increasing, and the manpower for operating the ground systems keeps being reduced, there is an increasing need for automating the health monitoring and status characterization of all on-board subsystems.

Goal: we present the first results of a joint study between KU Leuven and ESA aiming at finding new and efficient ways to automatically process spacecraft telemetry as it is down-linked. The goal is to detect anomalous behavior as well as early signs of new trends or discrepancies that are worth checking by an operations engineer. We aim at reducing the load on the flight control team while extending the “checkability” to the entire telemetry database, and provide efficient, faster and more accurate detection of anomalies in near real time. Special care is taken to define robust methods, i.e. to avoid false alarms as much as possible.

Means: we have performed a study of the statistical properties of the signal, regarding each parameter in the telemetry as an independent time series. We also analyzed binned time series of the signal properties themselves. Finally, we have completed the dataset with auxiliary parameters derived from the telecommand history, the event reports, the spacecraft attitude, etc.

For this study, we received a full year of Venus Express telemetry from

ESA, without description, enforcing a purely data-centric approach, without any a priori knowledge. We have developed and recommended a set of methods that were then validated against a second year of telemetry from Venus Express, namely the last one, where a series of peculiar operations took place before the mission was finally lost.

Results: We present a set of effective methods to (a) detect outliers in the telemetry or in its statistical properties, (b) uncover and visualize special properties of the telemetry and (c) detect new behavior. Our results are structured around two main families of solutions.

For parameters visiting a restricted set of signal values (i.e. all status parameters and about one third of all the others), we focus on a transition analysis. We show how Poincaré plots and transition probabilities can be used to uncover special properties of the signal and very efficiently detect anomalies and new behavior.

For parameters with an arbitrarily high number of possible signal values, we describe the statistical properties of the signal via its Kernel Density Estimate. We demonstrate that this allows for a generic and dynamic approach of the soft limit definition. Thanks to a much more accurate description of the signal and of its time evolution, the method provides more sensitive and much more responsive outlier detection capabilities than the traditional checks against hard limits.

The methods we present are generic for assisting in health monitoring of complex systems with large amounts of diagnostic sensor data. Not only spacecraft systems, but also present day astronomical observatories can benefit from using these techniques.

9910-59, Session 11

The evolution of observing modes at ESO telescopes

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Traditionally astronomers traveled to the telescopes to observe. With the start of space operations this has changed, and soon the large ground based observatories have followed along, introducing in addition to the traditional (visitor) also the service (in some observatories also known as queue) observing mode. When observing in service mode, the astronomers interact with the observatory staff who take the observations on behalf of the Principle Investigators and their team. The fundamental concepts behind these modes have not radically changed since they were introduced. However, the emergence of new scientific rationales and observing strategies and the will to take advantage of improving IT technologies have spawned new variants of these observing modes over the past 20 years. From the implementation of Service Mode at the NTT in 1997 to the recent “designated” Visitor Mode observations for short runs, we review how the palette of observing modes and the types of programs has evolved at ESO, responding to the requests of the user community. In more detail, we present how the evolution of tools at the disposal of external astronomers and the Observatory staff has enabled ESO to implement new types of observations (monitoring programs, time-constrained observations, rapid response mode, etc.) and to improve their efficiency. Also, we describe some of the challenges that are still ahead of us. Instruments currently in their construction or design phase, such as ESPRESSO or 4MOST, will once again shuffle the cards and force us to re-invent part of the operations and observation system to address the new constraints that these facilities bring. Scientific optimization of observing strategy including on-the-fly adjustments to the planned observations, or the necessity to multiplex several observing programs into a single slot of observing time will challenge our current implementation of flexible scheduling and will require solutions that do not jeopardize the rest of the observations. Recent feedback from the community has indicated that both visitor and service observing modes are highly rated for current and future observing sites, but that there is also interest for further evolution. In particular, we look at some first steps being done towards the possibility of performing remote observations at ESO telescopes: it is a perspective which has to be considered for the future, and one for which the user community has expressed clear interest.

9910-60, Session 11

New facilities, new challenges: the telescopes and instruments operators evolution

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Observatories and operational strategies are evolving in connection with the facilities that will be built. For those new facilities, the strategy for dealing with the telescopes, instrumentation, data-flow, reduction process and relationship with the community is more or less handled from its conception. However, for those Observatories already in place, the challenge is to adapt the processes and prepare the existing people for these changes.

The scope of this talk will show how Paranal Observatory is working by improving the continuous development of the Telescopes and Instruments Operator Group (TIO), preparing them with regards to the evolution of the instruments, operational techniques and the technical and engineering support for these new facilities.

When Paranal started with Science Operations activities during the late 1990s, the implemented operational model was standard among big observatories. All the technical procedural area about telescope operations was completely handled by Telescopes Operators and the activities related with the instrument (instrument acquisition and data acquiring, observational queues preparation, data quality control and calibrations completion) where mostly performed by the Astronomers on site.

Keeping in mind the requirements for more specific skills, the profile for selecting new TIOs and the involvement on operational activities changed during these years. With the implementation of the current operational scheme (SciOps 2.0), a more dynamic interaction culture between TIOs and Astronomers was born.

Today, Science Operations activities are directly handled by TIOs during daytime and nighttime. During nighttime, operational activities are performed collaboratively between astronomers and TIOs, and during the last part of the night, the Operators perform the full process independently. For those high level or more astrophysical dedicated decisions to be taken during the night, a Senior Astronomer (Nighttime Shift Coordinator) is always available at the Control Room, in order to keep offering the standard services of the Observatory. During daytime, the activities related with calibration completeness and data quality assurance are also part of the TIO duties.

Arriving to this level of involvement required the full support from the Observatory and the proactive support from Astronomers and other related groups under the Directorate of Operations.

This talk will show detailed information about current activities, the implemented training plan, the definition of the current operational model, the involvement of the group in projects towards improving in operational processes and efficiency, and what new challenges will be involved during the definition of the strategies for the new generation instruments to be installed.

9910-61, Session 12

Operations of the Thirty-Meter-Telescope (TMT) International Observatory

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The construction of the Thirty-Meter-Telescope International Observatory (TIO) is scheduled to take about eight years, with first-light currently planned for 2024 and start of operations soon after. Its innovative design, the unequaled astronomical quality of its location, and the scientific capability that will be offered by its suite of instruments, all contribute to position TIO as a major ground-based astronomical facility of the next decade.

In this talk, we will present the details of our operations plan, focusing in particular on the aspects of science operations and data-management, but describing as well our plans for managing technical operations, instrument development and logistics support.

After some initial periods dedicated to AIV and observatory commissioning, steady state operations will require a science and technical staff of about 120 persons. Daytime technical presence on the summit will address the support of all engineering and maintenance activities, while only a minimal nighttime crew will be present at the telescope to secure safe night-operations of the equipment. The telescope will be operated remotely at night from the TIO headquarters and science operations are expected to meet a wide range of observing needs. Observing support associated with ‘classical’ and ‘queue’ modes will be offered, including various flavors of remote observing, which will allow – when needed – ‘virtual’ (‘eavesdropping’) connection with the observatory staff by the team members of science programs. It is also planned that remote observing sites, operated by trained TIO staff, will be available across the partner countries. Such sites will support observation preparation, execution, and possibly data-reduction/analysis. The execution of the approved science programs will be implemented in the schedule in a manner to optimize scientific outputs. Science programs with stringent observing constraints, or time-critical components (e.g. ‘Target of Opportunity’ programs), will be fully supported as well. All science data, and their associated calibration frames, will be archived and available for download to the community of TIO users, and access to a wider community is currently being discussed.

The international TIO partnership includes Canada, China, India, Japan, Caltech, the University of California, and funding is also provided by the Gordon and Betty Moore Foundation. AURA is an associate member of TIO, on behalf of the US national community. Through a cooperative agreement with the NSF, TIO and a US-TMT Science Working Group are developing a model for potential US national partnership in the TIO.

9910-62, Session 12

Science operations at Gemini Observatory

Andrew J. Adamson, Gemini Observatory (United States); Rene Rutten, Gemini Observatory (Chile); Sandy Leggett, Gemini Observatory (United States)

Gemini Observatory operates two 8-m telescopes, one on Cerro Pachón in Chile and one on Maunakea Hawaii, supporting via a distributed model a multiple-member, international partnership. The telescopes, their software and supporting IT infrastructure (and some of the instrumentation) are identical at the two sites, affording economies of scale and staff-sharing opportunities in many technical and scientific areas. The aim of this paper is to describe the observatory’s operations in context of the >20% budget reduction incurred due to the withdrawal of the UK from the international partnership, other changes in the partnership itself and increasing use of short-term “limited-term partnership” arrangements via which interested potential full partners may “test the water”.

Recent initiatives such as the Large and Long Program and Fast Turnaround Program proposal modes, increased time for Visiting Instruments and the new Priority Visitor observing mode, have been successful from the point of view of the user community. We describe the integration of these initiatives into the regular operation and note some of the impacts which needed to be controlled.

Gemini operates a distributed user support model in which National Gemini Offices in each Partner country are responsible for a significant amount of user support, particularly in the early stages of the lifecycle of a science program. We discuss recent adjustments in this support model, driven by budget and effort constraints and the needs of the user community.

Finally, we describe science outcomes in terms of science program completion rates and publications, and make some comparisons with targets set early in the life of the observatory.

9910-63, Session 12

The 4MOST operations system

Tom Dwelly, Andrea Merloni, Max-Planck-Institut für extraterrestrische Physik (Germany); Jakob C. Walcher, Leibniz-Institut für Astrophysik Potsdam (Germany); Nicolas Clerc, Alain Gueguen, Thomas Boller, Max-Planck-Institut für extraterrestrische Physik (Germany); Roelof S. de Jong, Cristina Chiappini, Leibniz-Institut für Astrophysik Potsdam (Germany)

The 4MOST multi-object spectroscopic instrument to be mounted on the ESO/VISTA telescope will be used to conduct an ambitious multi-year wide area sky survey. A disparate set of science goals, requiring observation of tens of millions of galactic and extragalactic targets, must be satisfied by a unified program of observations. The 4MOST Operations System is designed to facilitate this complex task by i) providing sophisticated simulation tools that allow the science team to plan and optimise the 4MOST survey, ii) carrying out optimised medium-term scheduling using survey forecasting tools and feedback from previous observations, and iii) producing sets of observation blocks ready for execution at the telescope. We present an overview of the Operations System, highlighting the advanced facility simulator tool and the novel strategies that will enable 4MOST to achieve its challenging science goals.

9910-64, Session 12

Planning JWST NIRSpec MSA spectroscopy using NIRCam pre-images

Tracy Beck, Leonardo Ubeda, Diane M. Karakla, Susan Kassin, Space Telescope Science Institute (United States)

The Near-Infrared Spectrograph (NIRSpec) is the work-horse spectrograph at 1-5microns for the James Webb Space Telescope (JWST). A showcase observing mode of NIRSpec is the multi-object spectroscopy with the Micro-Shutter Arrays (MSAs), which consist of a quarter million tiny configurable shutters 0.”2x0.”45 in size. The NIRSpec MSA shutters can be opened in adjacent rows to create flexible and positionable spectroscopy slits on prime science targets of interest. Because of the very small shutter width, the NIRSpec MSA spectral data quality benefits significantly from very accurate astrometric knowledge of the positions of planned science sources. Images acquired with the Hubble Space Telescope (HST) have the optimal 5milli-arcsec accuracy for NIRSpec planning astrometry. However, galactic fields can have moderate proper motions beyond the 5mas source position knowledge, and extragalactic images with HST may have inadequate source information at NIRSpec wavelengths beyond 2 microns. Thus, optimal NIRSpec spectroscopy planning may require pre-imaging

observations with the Near-Infrared Camera (NIRCam) on JWST to properly establish source positions. We describe operational philosophies and programmatic considerations for acquiring JWST NIRCam pre-image observations for NIRSpec MSA spectroscopy planning within the same JWST observing Cycle.

9910-65, Session 12

Moving toward queue operations at the Large Binocular Telescope Observatory

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The Large Binocular Telescope Observatory (LBTO), a joint scientific venture between the Instituto Nazionale di Astrofisica (INAF), LBT Beteiligungsgesellschaft (LBTB), University of Arizona, Ohio State University (OSU), and the Research Corporation, is one of the newest additions to the world's collection of large optical/infrared ground-based telescopes. With its unique, twin 8.4m mirror design providing a 22.8 meter interferometric baseline and the collecting area of a 11.8m telescope, LBT has a narrow window of opportunity to exploit its singular status as the "first" of the next generation of Extremely Large Telescopes (ELTs).

Prompted by urgency to maximum scientific output during this favorable interval, LBTO recently re-evaluated its operations model and developed a new strategy that augments classical observing with queue. Run by trained observatory staff, queue mode will allow for flexible, multi-instrument observing responsive to site conditions. Our plan is to implement a staged rollout that will provide many of the benefits of queue observing sooner rather than late -- with more bells and whistles coming in future stages.

In this paper, we outline LBTO's new scientific model, focusing specifically on our "lean" resourcing and development, reuse and adaptation of existing software, challenges presented from our one-of-a-kind binocular operations, and lessons learned. We also outline further stages of development and our ultimate goals for queue.

9910-66, Session 12

4MOST: science operations for a large spectroscopic survey program with multiple science cases executed in parallel

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The 4MOST instrument is a multi-object spectrograph to be mounted to the VISTA telescope at ESO La-Silla-Paranal observatory. 4MOST will deliver several 10s of millions of spectra from surveys typically lasting 5 years. 4MOST will address Galactic and extra-galactic science cases simultaneously, i.e. by observing targets from a large number of different surveys within one science exposure. This parallel mode of operations as well as the survey nature of 4MOST require some 4MOST-specific operations features within the overall operations model of ESO. These features are necessary to minimize any changes to the ESO operations model at the La-Silla-Paranal observatory on the one hand, and to enable parallel science observing and thus the most efficient use of the instrument on the other hand.

I will describe the operations model for 4MOST as seen by the consortium building the instrument. Among others this encompasses: 1) A joint science team for all participating surveys (i.e. including community surveys as well as those from the instrument building consortium). 2) Common centralized tasks in observing preparation and data management. 3) Transparency of all decisions to all stakeholders. 4) Close interaction between science and facility operations. 5) Strategies to minimize complexity and coordination overhead.

Overall I will show that parallel observing mode is efficient, flexible, and manageable.

9910-67, Session 12

Optimizing parallel observations for the JWST/MIRI instrument

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Using unprecedented sensitivity and angular resolution, the Mid-Infrared Instrument (MIRI) for the JWST will provide imaging, coronagraphy, low-resolution slit spectroscopy, as well as integral-field spectroscopy at medium spectral resolution for a broad variety of science observations. Observing programs that use MIRI in parallel with other instruments (either as a prime or secondary instrument) are an optimal way to better exploit the observatory capabilities.

It is expected that the JWST operational observatory design will include parallel modes. We have therefore been studying the intricacies of combining MIRI (5-28 microns) and NIRCam (0.6-5microns) imaging observations for a deep imaging use-case. Such programmes present particular challenges from an operations point of view.

These collaborative programs pose some interesting challenges from the operations point of view. New dither patterns need to be designed that optimally work for both instruments and take into account their individual detector characteristics, field of views and relative orientations. They also need to consider the difference in PSF between instruments. The MIRI PSF is Nyquist sampled at wavelengths larger than about 6.3 microns, and sub-pixel sampling may be needed for the shorter wavelengths. For the long wavelengths, ideally dithers should be of the order of 2 or 3 FWHM. NIRCam will need sub-pixel sampling for for almost all wavelengths bluer than 2 microns in the Short wavelength detector and 4.4 microns in the Long wavelength one.

From a purely operational perspective, the way instrument events are planned and organized (e.g. changing filter wheels) needs to be taken into account as well; one instrument's mechanisms cannot be moved while other is exposing. In this sense the dwelling time on each dither position is another aspect to consider. For MIRI, the detector performance and the radiation environment at the L2 orbit will dictate for how long we can integrate on each dither position.

All this, along with the difference in sensitivity between instruments, (e.g. MIRI does not reach as deep as NIRCam for a given exposure time) are the main drivers for the design of joint science programs.

In general the design and execution of MIRI parallel observations needs to be carefully choreographed, and that requires close collaboration and compromise with other instrument teams. In this contribution we present the overall design of the MIRI observations in parallel with NIRCam, opening the path to a wealth of collaborative science opportunities between MIRI and the rest of JWST instruments.

9910-68, Session 12

Through thick and thin: quantitative classification of photometric observing conditions on Paranal

Florian Kerber, European Southern Observatory (Germany); Richard R. Querel, National Institute of Water and Atmospheric Research (New Zealand); Bianca Neureiter, Ludwig-Maximilians-Univ. München (Germany); Reinhard Hanuschik, European Southern Observatory (Germany)

A Low Humidity and Temperature Profiling (LHATPRO) microwave radiometer is used to monitor sky conditions over ESO's Paranal observatory. It provides measurements of precipitable water vapour (PWV) at 183 GHz, which are being used in Service Mode for scheduling observations taking advantage of favourable conditions for infrared observations. The instrument also contains an IR camera measuring sky brightness temperature at 10.5 ?m. It is capable of detecting very cold and very thin, even sub-visual, cirrus clouds. We present a diagnostic diagram that, based on a sophisticated time series analysis of these IR sky brightness data, allows for the automatic classification of photometric observing conditions over Paranal. The method is highly sensitive to the presence of even very thin clouds but robust against other causes of sky brightness variations. The diagram has been validated across the complete range of conditions that occur over Paranal and we find that the automated process provides correct classification at the 95% level.

9910-69, Session 12

A daily task manager for Paranal science operations

Cristian M. Romero, Steffen Mieske, Stéphane Brillant, European Southern Observatory (Chile); Myriam Rodrigues, Observatoire de Paris à Meudon (France); Andres Pino, Leonel Rivas, European Southern Observatory (Chile)

Paranal Observatory has a department called Science Operations and is in charge of operates the instrument within the global scheme established for the Very Large Telescope. This scheme was improved on what was called SciOps 2.0. The main operational goals of this new scheme were strengthen the coordination of science operations activities within, and between, the department groups, by increasing the time allocated to "high-level" activities. Also improve the efficiency of the core science operations support to service mode (SM) and visitor mode (VM) observations, and the quality of the astronomical data delivered to the community of Paranal users.

In this context of efficiency and quality improvement of operations within the SciOps department, we had identified a strong need to optimize the management of daily operation tasks, via the development of a daily activity monitoring integrated tool, so this paper details the findings of the Daily Activity Monitoring Integrated Tool (DAMIT), the proof of Concept phase and the first delivered phase. The technical proof of concept was the first phase in development of a daily operation-monitoring tool for the science operation department. The primary objective of this phase was to evaluate the viability and impact of such a tool to improve the quality and efficiency of SciOps at Paranal.

We present the preparation of this study followed an on-site technical analysis of the SciOps daily operation (day and night), the current procedures to certify the completeness and quality of the daily operations, and requirements for a new daily operation-monitoring tool.

9910-71, Session 12

Delivering data reduction pipelines to science users

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The ultimate objective of astronomical observations is to produce science data products that can be used to extract science. The complexity of modern instruments requires highly specialized algorithms for data organization and data reduction. Data visualization and user interaction, both to fine tune individual algorithms and to modify the data flow itself, are essential for the production of science grade products that fully exploits the potential of the raw data.

The European Southern Observatory has a long history of providing specialized algorithms called recipes for each of its instruments. However, calling these recipes in sequence and providing the proper input to each of the recipes is a challenging and time consuming task. The efficiency of data reduction can vastly be improved by using automatic workflows to organise data and execute a sequence of data reduction steps. To realize such efficiency gains, we designed a system called ESOREFLEX that allows intuitive representation, execution and modification of the data reduction workflow, and has facilities for inspection of and interaction with the data. ESOREFLEX uses a number of innovative concepts and has been described in Freudling et al., 2013, Astronomy and Astrophysics 559, 96. In October 2015, the complete system was released to the public. It includes systems for automatic data organization and visualization, interaction with recipes, and the exploration of the provenance tree of intermediate and final data products. ESOREFLEX is highly efficient, using its internal bookkeeping database to recognize and skip previously completed steps during subsquent processing of the same or similar data sets.

ESOREFLEX workflows encapsulate the best practice data reduction for the data from a particular instrument mode, and at the same time can easily be modified by users. Where necessary, several alternative reduction flows are offered in a single workflow. Currently, about 20 different workflows for most of the instruments on ESO's Very Large Telescope (VLT) have been released or are under development.

ESOREFLEX executes the same recipes that have been developed for other operational purposes, such as data quality control and archive processing.These highly controlled operational environments have substantially different requirements. In particular, they run these recipes mostly unsupervised in a static manner. ESOREFLEX allows to deliver these operational pipelines to science users that use them in a highly interactive and dynamic manner.

Conference 9911: Modeling, Systems Engineering, and Project Management for Astronomy VI

Sunday - Tuesday 26–28 June 2016

Part of Proceedings of SPIE Vol. 9911 Modeling, Systems Engineering, and Project Management for Astronomy VI

9911-1, Session 1

Daniel K. Inouye Solar Telescope: the latest integration, testing, and commissioning plan

Simon C. Craig, Kerry L. Gonzales, Robert P. Hubbard, Chang Liang, Ruth A. Kneale, William R. McBride II, Predrag Sekulic, Timothy R. Williams, National Solar Observatory (United States)

The Daniel K. Inouye Solar Telescope (DKIST) has been in its construction phase since 2010, anticipating the onset of the integration, test, and commissioning (IT&C) phase in early 2017, and the commencement of science verification in 2019. The works on Haleakal? are progressing at a phenomenal rate and many of the various sub-systems are either through or about to enter their Factory (or Laboratory) acceptance. The delays in obtaining site planning permissions, while a serious issue for Project Management, has allowed the sub-systems to develop well ahead of their required delivery to site. We have benefited from the knowledge that many sub-systems will be on site and ready for integration well before affecting the critical path. Opportunities have been presented for additional laboratory/factory testing which, while not free, significantly reduce the risks of potential delays and rework on site. From the perspective of IT&C this has provided an opportunity to develop the IT&C plans and schedules free from the pressures of imminent deployment.

In this paper we describe the ongoing planning of the Integration, Testing and Commissioning (IT&C) phase of the project in particular the detailed planning phase that we are currently developing.

9911-2, Session 1

Two years of nominal science operations: experiences from the Gaia science ground segment

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With its launch at the very end of 2013, ESA's astrometry satellite Gaia began its endeavor to compile astrometric and photometric measurements of at least one billion objects, as well as high resolution optical spectra of hundred million objects. The Gaia catalog therefore results in a wealth of coherently determined astrophysical parameters of these objects.

After its extensive commissioning phase, Gaia entered the nominal mission phase in July 2014. The science ground segment, which is formed by the Gaia Data Processing and Analysis Consortium (DPAC), has since then started its operations. DPAC is a large, multi-national, science consortium which has to handle and process the dense and complex Gaia data stream. With its decentralized management and its distributed infrastructure, the Gaia DPAC is a remarkable undertaking. In this paper we will summarize some of the experiences of the DPAC facing the real Gaia data, compare this to the pre-launch expectations, and critically review the development phase. By comparing the pre-launch expectations with the real life experiences, we will draw the limitations of a requirements driven development approach for such large scale science software projects, in particular in view of the human factor.

9911-3, Session 1

The Large Synoptic Survey Telescope (LSST) materials test facility (MTF)

David K. Gilmore, Aaron J. Roodman, Kevin A. Reil, Tim Bond, SLAC National Accelerator Lab. (United States)

This paper outlines the design, construction and performance of the Large Synoptic Survey Telescope (LSST) camera Materials Test Facility (MTF) that was built and developed at Stanford/SLAC/KIPAC in compliance with government, industry standards and specifications to ensure that the contamination-critical and sensitive items in the LSST Camera are fabricated, assembled and operated in a way that reduces the likelihood of damage or loss of function due to contamination.

The Large Synoptic Survey Telescope (LSST) project is the most ambitious currently planned in the optical wavelengths. A vast array of science will be enabled by this single wide-deep-fast sky survey, and LSST will have unique survey capability in the faint time domain. The telescope will have an 8.4m (6.5m effective) primary mirror, a 9.62 field of view and a 3.2 gigapixel camera. The system is designed to yield high image quality as well as supurb astrometric and photometric accuracy. To achieve these goals, part of the design requires that the electronics for the camera CCDs operate at -40C inside the cryostat. Given over 3K video channels, each of the 82 electronics boards contain over 1800 active and passive components, along with many connectors and cables that could compromise data quality by deposition of molecular contaminants on the surface of the 4kx4k 201 CCDs in the focal plane as well as the vacuum side of the 1m cryostat window.

Molecular contamination on focal plane CCDs is a major potential source of uncertainty for any astronomical camera performance. This paper seeks to gain leverage on this issue by directly measuring the molecular outgassing rates, at a very sensitive level (10-13 torr), of electronic components, connectors, cable and mechanical assemblies and a fully populated electronics board. The resultant analysis of the MTF data will inform the LSST camera instrument model which is of paramount importance for analyzing eventual LSST throughput data and selection of low outgassing materials.

The LSST MTF is a UHV system designed to measure two types of contamination levels, rate-of-rise and throughput with a conductance (or orifice). On each side of the conductance, the system contains a Stanford Research System 200amu Residual Gas Analyzer (RGA), a 20l s-1 ion pump, and a 200l turbo pump. The system also has the provision for plasma cleaning which involves the removal of impurities and contaminants from surfaces through the use of an energetic plasma created from gaseous species (the LSST MTF uses hydrogen and oxygen).

The prioritized risk scenarios for the LSST camera contamination levels based on the effect on performance and the difficulty of recovery from a "contamination event" are:

1. Non-Evaporable Residue (NVR-molecular contamination) in the vacuum of the cryostat that accumulates on critical surfaces (input window lens surface and sensor surfaces).

2. Accumulation of condensable materials on optical surfaces that are cold relative to their surrounding environment (water on sensor surfaces or the first or second surfaces of the input window lens).

3. Non-evaporable substances that accumulate on optical or CCD surfaces.

4. Accumulation of particulate matter on optical or CCD surfaces.

Quantitative analysis of contamination levels and the effect on camera performance is used to define milestone cleanliness and exposure durations of the critical components. Such analysis is also used to establish cleanliness requirements for associated sensitive hardware.

This paper will describe the detailed design and implementation of the LSST MTF, review the various configurations and procedures involved with making high precision RGA measurements, explain the rationale and results of plasma cleaning and give an overall evaluation of cryostat measured, in-situ component outgassing rates.

9911-4, Session 1

Mission-level performance verification approach for the Euclid space mission

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ESA's Dark Energy Mission Euclid will map the 3D Dark Matter distribution by measuring two Dark Energy probes: Weak Lensing (WL) and Galaxy Clustering (GC). The extreme accuracy required for both probes can only be achieved by observing from space in order to limit all observational biases in the measurements of tracer galaxies. Weak Lensing requires an extremely high precision measurement of galaxy shapes realised with the Visual Imager (VIS) as well as photometric redshifts using near-infrared photometry provided by the Near Infrared Spectrometer Photometer (NISP) complemented by additional ground based visible photometry. Galaxy Clustering requires very accurate redshift measurements (0.1%) of galaxies to be obtained by the NISP Spectrometer.

Performance requirements on spacecraft, telescope assembly, scientific instruments and the ground data-processing have been carefully budgeted to meet the very demanding top level cosmology requirements. As part of the mission development, the verification of scientific performances needs mission level end-to-end analyses in which the Euclid systems are modelled from as-designed to final as-built flight configurations. We present the plan to carry out end-to-end analysis coordinated by the ESA project and the Euclid Consortium in collaboration, including the definition of key performance parameters and their process of verification, the input and output identification and the management of applicable mission configurations in the parameter database.

9911-5, Session 1

Bottom-up laboratory testing of the DKIST Visible Broadband Imager (VBI)

Andrew Ferayorni, Andrew Beard, B. Scott Gregory, Wes Cole, Friedrich Wöger, National Solar Observatory (United States)

The Daniel K. Inouye Solar Telescope (DKIST) is a 4-meter solar observatory under construction at Haleakala, Hawaii. The Visible Broadband Imager (VBI) is a first light instrument that will record images at the highest possible spatial and temporal resolution of the DKIST at a number of scientifically important wavelengths. The VBI is a pathfinder for DKIST instrumentation and a test bed for developing processes and procedures in the areas of unit, systems integration, and user acceptance testing. These test procedures have been developed and repeatedly executed during VBI construction in the lab as part of a "test early and test often" philosophy aimed at identifying and resolving issues early thus saving cost during integration test and commissioning on summit.

The VBI team recently completed a bottom up end-to-end system test of the instrument in the lab that allowed the instrument's functionality, performance, and usability to be validated against documented system requirements. The bottom up testing approach includes four levels of testing, each introducing another layer in the control hierarchy that is tested before moving to the next level. First the instrument mechanisms are tested for positioning accuracy and repeatability using a laboratory position-sensing detector (PSD). Second the real-time motion controls are used to drive the mechanisms to verify speed and timing synchronization requirements are being met. Next the high-level software is introduced and the instrument is driven through a series of end-to-end tests that exercise the mechanisms, cameras, and simulated data processing. Finally, user acceptance testing is performed on operational and engineering use cases through the use of the instrument engineering graphical user interface (GUI).

In this paper we present the VBI bottom up test plan, procedures, example test cases and tools used, as well as results from test execution in the laboratory. We will also discuss the benefits realized through completion of this testing, and share lessons learned from the bottoms up testing process.

9911-6, Session 2

Gaia challenging performances verification: combination of spacecraft models and test results *(Invited Paper)*

Eric Ecale, Frederic Faye, François Chassat, Airbus Defence and Space (France)

To achieve the ambitious scientific objectives of the Gaia mission, extremely stringent performance requirements have been given to the spacecraft contractor (Airbus DS). For a set of those key-performance requirements (e.g. end-of-mission parallax, maximum detectable magnitude, maximum sky density or attitude control system stability), this paper describes how they are engineered during the whole spacecraft development process, with a focus on the end-to-end performance verification. As far as possible, performances are usually verified by end-to-end tests on-ground (i.e. before launch). However, the challenging Gaia requirements are not verifiable by such a strategy, principally because no test facility exists to reproduce the expected flight conditions. The Gaia performance verification strategy is therefore based on a mix between analyses (based on spacecraft models) and tests (used to directly feed the models or to correlate them). Emphasis is placed on how to maximize the test contribution to performance verification while keeping the test feasible within an affordable effort. In particular, the paper highlights the contribution of the Gaia Payload Module Thermal Vacuum test to the performance verification before launch. Eventually, an overview of the in-flight payload calibration and in-flight performance verification is provided.

9911-7, Session 2

Integration and verification testing of the Large Synoptic Survey Telescope camera

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We present an overview of the Integration and Verification Testing (I&T) activities of the Large Synoptic Survey Telescope (LSST) Camera at the SLAC National Accelerator Lab (SLAC). The LSST Camera, the sole instrument for LSST and under construction now, is comprised of a 3.2 Giga-pixel imager and a three element corrector with a 3.5 degree diameter field of view. LSST Camera I&T will be taking place over the next five years with final delivery to the LSST observatory anticipated in early 2020. We outline the planning for I&T, describe some of the key verification hardware systems being developed, and identify some of the more complicated assembly/integration activities. Specific details of integration and verification hardware systems will be discussed, highlighting some of the technical challenges anticipated.

9911-8, Session 2

OAJ 2.6m survey telescope: optical alignment and on-sky evaluation of IQ performances

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AMOS has recently completed the alignment campaign of the 2.6m telescope for the Observatorio Astrofisico de Javalambre (OAJ). Installed on the Pico del Buitre (Aragon, Spain), the telescope is primarily intended to be used for deep-sky photometric surveys. It is equipped with two mirrors, which are arranged in a Ritchey-Chretien configuration, and with a three-lens aspherical field-corrector. It exhibits a wide field-of-view of +/- 1.5° associated to a large aperture of 2.6m that endow the telescope with a large etendue.

Due to its low focal-ratio (f/# = 3.5), the alignment of the telescope is a complex and challenging process that aims at providing an outstanding image quality over the focal plane of 500mm diameter. In order to reach that optical quality, the positions of the secondary mirror and of the instrument focal plane are adjustable with the help of dedicated hexapods. In that framework, AMOS developed an innovative alignment technique for wide field-of-view telescopes that has been successfully implemented on the OAJ 2.6m telescope with the active support of the team of CEFCA (Centro de Estudios de Física del Cosmos de Aragón).

The alignment relies on two fundamental techniques: (1) the wavefront-curvature sensing (WCS) for the evaluation of the telescope aberrations at arbitrary locations in the focal plane, and (2) the coma-free point method for the adjustment of the position of the secondary mirror (M2) and of the focal plane (FP). The wavefront curvature sensing technique consists in reconstructing the telescope wavefront error from the measurement of the intensity of two out-of-focus images of a star, while the alignment with the coma-free point method allows to perform a sequential alignment of the telescope, with a step-by-step minimization of independent aberrations (coma, field-astigmatism, spherical aberration and focus). Since it does not require the use of traditional Shack-Hartmann wavefront sensors, the proposed method can be readily implemented in any telescope focal plane at a reasonable cost.

For the alignment and commissioning purposes, a dedicated verification camera is installed on the focal plane of the 2.6m telescope. The verification camera features two off-the-shelf CCD sensors that are mounted on two translations stages. The sensors can be positioned at any locations in the focal plane and are able to move along the optical axis. The verification camera thus allows to perform intra- and extra-focal image acquisitions for the WCS, as well as an assessment of the image quality in the telescope focal plane.

The alignment campaign unfolded in three steps: (a) analysis of the repeatability of the WCS measurements, (b) assessment of the sensitivity of telescope WFE to M2 and FP position adjustments, (c) optical alignment of the telescope and (d) evaluation of image quality in the overall focal plane. At the end of the campaign, seeing-limited performances were easily demonstrated in the complete focal plane. With the help of CEFCA team, the image quality of the telescope has been further investigated with a lucky-imaging method. Image sizes of less than 0.3 arcsec FWHM are obtained, and this excellent image quality is observed over the complete focal plane.

9911-9, Session 2

Limiting JWST momentum accumulation: strategies and simulation results

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On the James Webb Space Telescope (JWST) mission, the Observatory's large sunshield and uncertainty about exact center of mass makes momentum management a major operations challenge. As observations are executed at different attitudes, varying pitch and roll torques cause momentum buildup, requiring occasional propulsive maneuvers to unload momentum. The JWST propulsion system is sized for a 10-year science mission. Depending on still-uncertain torque magnitudes, momentum unloads could be needed as frequently as once a week on average, making momentum buildup reduction an important operations objective to improve efficiency and extend mission lifetime. JWST uses a two-phase planning and scheduling system. First, observations are assigned to limited "plan windows" (typically 10-60 days) based on a variety of constraints and criteria. Next, short-term scheduling proceeds using the subset of candidates whose plan windows overlap a ~1-week scheduling interval. Several strategies are available to limit momentum buildup. These include momentum balancing during long-range planning, momentum balancing during short-term scheduling, and (to the extent that science constraints permit) adjustments to Observatory orientation. With development of the operational JWST planning and scheduling system, empirical investigation has become possible using realistic mission simulations that vary these strategies. This paper presents results of mission simulations using the Science Operations Design Reference Mission (SO-DRM), a scientifically diverse suite of programs resulting in over 10,000 schedulable units (visits), which have been performed to compare the effectiveness of the above momentum reduction strategies over ~1-year intervals. Detailed investigation is continuing, but scheduling experiments have already demonstrated significant reductions in momentum buildup. Balancing observations during long-range planning appears the most powerful approach because this is the phase with the most global view of the pool of schedulable visits and can generate well-balanced sets of plan windows that facilitate short-term optimization. However, effective short-term scheduling strategies are also essential. For optimal results, all three of the above approaches should be pursued in combination.

9911-10, Session 2

Earthquake survivability tests and analysis for a Thirty Meter Telescope primary segment assembly

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Shake tests were conducted January 2015 in El Segundo, California of a single Primary Segment Assembly to verify compliance with earthquake

survivability requirements for a 200 Average Return Period earthquake. The test results were also used to validate a dynamic model of combined response of the segment and soft actuators. Both the model and extrapolation of the data were used to predict compliance of earthquake survivability requirements for 1000 Average Return Period earthquake. Requirements for acceleration at the mirror surface in both the vertical and horizontal directions are based on buckling limits and safety factors. The soft actuators that control piston and tip-tilt motion of the mirror surface amplify earthquake vertical acceleration at the mirror cell resulting in larger acceleration at the mirror surface. A snubber limits the travel of the soft actuator, which thereby limits the acceleration at the mirror surface, but the dynamic interaction is complicated, and testing was considered to be necessary. The test results and analysis verified compliance with earthquake survivability requirements. The test results, dynamic model, and model-based predictions will be presented. Diagrams of the vertical and horizontal test setup are shown in Figure 1. A short movie of the shake test will be presented.

9911-11, Session 3

Creating system engineering products with executable models in a model-based engineering environment *(Invited Paper)*

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The system engineering life-cycle creates a number of products built from interdependent sources of information using different kinds of system level analysis. This paper focuses on leveraging the Executable System Engineering Method (ESEM) that automates some system level analysis (e.g. requirements verification, power and mass budget margins, duration analysis of operational modes) using executable SysML modeling patterns that involve structural, behavioral and parametric diagrams, and the open source Model Based Engineering Environment (openMBEE).

Executable system models provide the data to create required products (e.g. operational concept document) for the Alignment and Phasing System (APS) within the Thirty Meter Telescope (TMT), under development by the TMT International Observatory (TIO).

9911-12, Session 3

Model-based system engineering approach for the Euclid mission to manage scientific and technical complexity

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In the last years, the system engineering field is coming to terms with a paradigm change in the approach for complexity management. Different strategies to cope with highly interrelated systems, system of systems and collaborative system engineering have been proposed and a significant effort is in place into standardization and ontology definition. In particular, Model Based System Engineering (MBSE) intends to introduce methodologies for a systematic system definition, development, validation, deployment, operation and decommission based on logical and visual relationship mapping, rather than traditional 'document based' information management.

The practical implementation in real large-scale projects is not uniform across fields. In space science missions the usage has been limited to subsystems or sample projects with modelling performed 'a-posteriori' in many cases. The main hurdle for the introduction of MBSE practices in new projects is still the difficulty to demonstrate the value added to a project and whether the benefit is commensurate with the level of effort required.

In this paper we present the implemented Euclid modelling activities, and the benefits identified to support in particular requirement break-down and allocation and verification planning at mission level.

Euclid is the second medium class mission (M2) of the ESA Cosmic Vision program. Its primary goals are to determine the nature and distribution of dark matter and dark energy using two main cosmological probes: Weak Lensing (WL) and Galaxy Clustering (GC). These objectives plan to be achieved with a survey of more than 15,000 deg2 of the extragalactic sky performed by a single spacecraft with a 1.2 m entrance pupil telescope equipped with a visible imager (VIS) and a near infrared spectrophotometer (NISP). The WL probe involves the measurement of galaxy shear of a large number of sources, driving performance requirements beyond traditional image quality and sensitivity to include also ellipticity, PSF stability and control of any systematic bias that could introduce errors in the cosmological signal of interest. The required level of residual errors depends not only on the performance of the telescope, instruments, spacecraft pointing, etc, but also to a significant extent on calibration data, external data (from other space and/or ground missions) and the science data processing algorithms performance. These different contributors are developed and under responsibility of different entities both within ESA project and its direct contractors and as part of a Euclid Consortium composed of institutions across different nations.

The complex interrelationship between the different contributors to the system performance and the number of involved stakeholders led early to the decision to adopt a MBSE approach in Euclid to control requirement flow-down, architecture selection, verification and operations definition. Specifically System Modelling Language (SysML) was selected to build a representation of the system and capture the complete traceability of the mission break-down from science objectives to verification and full life-cycle planning.

This is, to our knowledge, the first full application of MBSE in an ESA science project in development and it has generated an important number of lessons learned and recommendations for modelling in future missions that will be presented.

9911-13, Session 3

Using model based systems engineering for the development of the Large Synoptic Survey Telescope's (LSST) concept of operations

Brian M. Selvy, Charles Claver, LSST (United States)

In this paper we provide an overview of the methodology and tools we are using to develop the concept of operations (ConOps) for operational phase of the Large Synoptic Survey Telescope (LSST). LSST's Project Systems Engineering (PSE) team's is using a model-based approach ConOps development to: 1) capture the top-down stakeholders' needs and functional allocations defining the scope, required tasks, and personnel needed to for operations, and 2) model a bottom-up, Use Case-driven approach capturing known operations and maintenance activities required to conduct the LSST survey across its distributed operations sites for the full ten year survey duration. The top-down view is being used to support a team writing the operations proposal, where the bottom-up view will be used in the future as the basis for developing the detailed work procedures required to by each activity. To accomplish these complimentary goals

and ensure that they result in self-consistent results, we have developed a holistic approach using the Sparx Enterprise Architect modeling tool and Systems Modeling Language. This approach utilizes SysML Use Cases, Actors, associated relationships, and Activity Diagrams to document and refine all of the major operations and maintenance activities that will be required to successfully operate the observatory and meet stakeholder expectations. Additionally, we have customized the tool and extended the SysML language to meet the our unique needs; customizations that have resulted in the creation of a custom stereotyped Use Case element with unique tagged values, as well as unique association connectors and actor stereotypes. Our approach allows for continual refinement utilizing the systems engineering spiral method to expose higher levels of detail as necessary. We demonstrate the methodology described here, has the ability to define: 1) the rolls each human actor must take on to successfully carry out the activities associated with the Use Cases; 2) the skills each actor must possess; 3) the functional allocation of all required stakeholder activities and use cases to organizational entities tasked with carrying them out; and 4) the organization structure required to successfully execute the operational survey.

9911-14, Session 3

Operational modes, health, and status monitoring

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System Engineers must fully understand the system, its support system and operational environment to design & develop a system. Support & Maintenance Managers must also identify the correct metrics to measure the performance and manage the support organisation.

Model-based Systems Engineering (MBSE) is a systems engineering methodology which focuses on creating models as the means of information exchange. Logistic Engineering and Support Analysis provides methods to design a Support & Maintenance System and to optimize the Operational Availability of a complex system. Availability modeling and Failure Analysis during the design is intended to influence the design and to develop an optimum maintenance strategy for a system.

The remote site locations of the SKA Telescopes place emphasis on availability and Failure identification information is critical to the success of the project.

This paper describes the used of MBSE on the SKA project to model the Telescope's operational modes and health monitoring information. It describes the use of Failure Analysis and a Support Database to design a Support & Maintenance strategy. It also describes the used of modeling to develop an availability dashboard and performance metrics.

9911-15, Session 4

Optical error budgeting using linearized ray-trace models

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Design of optical telescopes and instruments increasingly relies on "STOP" modeling methods, which combine detailed structural, thermal, and optical models to generate realistic simulated data and make accurate system performance predictions. By also incorporating models of key mechanisms, actuators, alignments, and closed-loop controls, such models can accurately predict the impact of component and subsystem errors on total system performance. STOP models can be very time consuming to create and exercise, however, making them inefficient for common system design and engineering tasks such as error budgeting.

We present the mathematical framework for an alternative approach that preserves the accuracy of the full-up STOP model, but in a computationally efficient spreadsheet form. The method builds on earlier work in linearized ray-trace methods [1]. It directly incorporates system kinematics, alignments, sensors and controls, and other key elements. It propagates statistical representations of component and subsystem errors, misalignments and aberrations, to compute metrics such as wavefront error, Strehl ratio, encircled energy, and line-of-sight error, as a function of design and error specifications.

Examples from space and ground-based active telescopes illustrate the approach.

Reference

[1] D. Redding and W. Breckenridge, "Linearized Ray-Trace Analysis," Selected SPIE Papers on CD ROM, Volume 2, Lens Design, D. O'Shea, ed., 1998.

9911-16, Session 4

Systems budgets architecture and development for the Maunakea Spectroscopic Explorer

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The Maunakea Spectroscopic Explorer (MSE) project is an enterprise to upgrade the existing Canada-France-Hawaii observatory into a spectroscopic facility based on a 10 meter-class telescope. As such, the project relies on engineering requirements not limited only to its instruments (the low, medium and high resolution spectrographs) but for the whole observatory. The science requirements, the operations concept, the project management and the applicable regulation are the basis from which these requirements are initially derived, yet they do not form hierarchies as each may serve several purposes, that is, pertain to several budgets. Completeness and consistency are hence the main systems engineering challenges for such a large project as MSE. Special attention is devoted to ensuring the traceability of requirements via parametric models, derivation documents, simulations, and finally maintaining KAOS diagrams and a relational database under IBM Rational DOORS® linking them together. This paper will present the architecture of the main budgets under development and the associated processes, expand to highlight those that are interrelated and how the system, as a whole, is then optimized by modelling and analysis of the pertinent system parameters.

9911-17, Session 4

Automatic performance budget: a global process for instrumentation

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Whatever the wavelength domain, projects in astronomy evolve towards larger dimensions and higher complexity. In the meantime, risks in terms of safety, cost and operability have to be reduced to the minimum, to maintain a reasonable maintenance cost, while the time to perform the different phases shortens. From the system engineer point of point, this evolution is an important challenge. Big instruments imply to manage interfaces within large consortia and to deal with the time dedicated for the design phases which necessitates having an efficient and rapid interaction between all the stakeholders to ensure that the design fits all the requirements. Such an interaction is mandatory to rapidly answer any question of the engineer and maximising the time devoted to the design.

In this context, tools can participate to provide solutions. We present in the

first section the development of an automatic performance budget that helps the system engineer to estimate in a few minutes how a change in the design may impact the scientific performance. This capability without the help of simulations during the phase A allows a faster interaction between, first, the engineers and the system engineer and, secondly, between the latter and the instrument scientist on the other hand. We summarise in a second section how tobuild an automatic performance budget while in the three following sections the examples of EAGLE, MOONS and SST-GATE are described in order to illustrate how this mechanism has been used in projects in astronomy.

9911-18, Session 4

E-ELT requirements flow from top-level requirements through level 1 requirements down to procurement specifications

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One of the critical activities in the systems engineering scope of work is managing requirements. In order to be able to implement the system and attending not only to technical but also to programmatic aspects, systems engineering has to split the whole thing in several parts that have to match each other to fulfil the user needs. Properly specifying these parts (that are procured separately) to make sure that they will run as a whole when integrated together is not an easy task, in particular when dealing with complex systems.

In line with this, E-ELT systems engineering devotes a significant effort to this activity, which follows a well-established process. The goal is to optimally derive requirements from the user (Top-Level Requirements) through the system Level 1 Requirements and from here down to subsystems procurement specifications.

This papers describes the process, which is illustrated with some practical examples. To help in understanding this process, the E-ELT documentation tree, showing the relationship between the several requirements specifications at different levels, is presented. Particular attention is given to the Level 1 Requirements specification, which is the highest level engineering document describing the actual baseline of the E-ELT. To provide the complete picture a short overview of its parent document (Top-Level Requirements) and of a typical (children) subsystem specification is given.

The special role of the technical budgets as tools to manage the critical Top-Level Requirements and to derive requirements on subsystems is also addressed. To better understand this role a summary of the technical budgets that are maintained at system level is given.

In addition, the way that requirements specifications are reviewed as the final step before releasing for procurement is explained. To close the process, the provisions taken at system and subsystem level for the verification of requirements along the several milestones of the procurement contracts are discussed.

Apart from the already mentioned technical budgets, other tools helping in the requirements management process (e.g., database, review files, compliance matrix) and the way they are used is described.

9911-19, Session 4

DESI systems engineering: throughput and signal-to-noise

Robert W. Besuner, Univ. of California, Berkeley (United States)

The Dark Energy Spectroscopic Instrument (DESI) is under construction to measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of tens of millions of galaxies over 14,000 square degrees will be measured over the planned five-year survey. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs.

Managing light throughput and noise in all elements of the instrument is key to achieving the high-level DESI science requirements over the planned survey area and depth within the planned survey duration. The DESI high-level science requirements flow down to instrument performance requirements on system throughput and operational efficiency. Signal-to-noise requirements directly affect minimum required exposure time per field, which dictates the pace and duration of the entire survey. The need to maximize signal (light throughput) and to minimize noise contributions and time overhead due to reconfigurations between exposures drives the instrument subsystem requirements and technical implementation.

Throughput losses arise from several effects, including blurred galaxy images, lateral misplacement of galaxy images relative to fiber tips, losses at air/glass interfaces, reflection and transmission losses in optics and fibers, fiber focal ration degradation (FRD), diffraction grating inefficiency, and CCD quantum efficiency. Throughput losses are managed with subsystem requirements on: optics manufacturing and alignment tolerances; fiber positioner accuracy; system structural stability; guiding accuracy; transmission and reflectivity of optics; fiber system FRD; and spectrograph and CCD performance.

Noise contributors include stray light and ghosts, night sky background light, and CCD read noise. Mitigation of noise is achieved by requirements on: design of optics and baffling based on ghosting and stray light analysis; corrector f-ratio and fiber diameter optimized to balance maximizing galaxy light while minimizing sky background; and CCD and readout electronics noise.

The interexposure time is minimized by choreography of the entire reconfiguration sequence and with specific time requirements on: CCD readout; telescope slewing and settling; fiber positioner reconfiguration; corrector hexapod motion; and atmospheric dispersion compensator re-alignment.

Throughput, noise, and interexposure reconfiguration time are budgeted, tracked, and managed as a DESI Systems Engineering responsibility. Current best estimates of throughput losses and noise contributions from each individual element of the instrument are tracked together in a master budget to calculate overall margin on completing the survey within the allotted time.

9911-21, Session 5

Project management and control of the Daniel K. Inouye Solar Telescope (DKIST) *(Invited Paper)*

Joseph P. McMullin, Mark Warner, Thomas R. Rimmele, Simon C. Craig, Andrew Ferayorni, Bret D. Goodrich, Robert P. Hubbard, Rex Hunter, Paul Jeffers, Erik M. Johansson, Heather Marshall, William R. McBride II, William McVeigh, LeEllen Phelps, Steve Shimko, Alexandra Tritschler, Timothy R. Williams, Friedrich Wöger, National Solar Observatory (United States)

We provide a brief update on the construction status of the Daniel K. Inouye Solar Telescope, a $344M, 10-year construction project to design and build the world's largest solar physics observatory. We review the science drivers along with the challenges in meeting the evolving scientific needs over the course of the construction period without jeopardizing the systems engineering and management realization. We review the tools, processes and performance measures in use in guiding the development as well as the risks and challenges as the project transitions through various developmental phases. We elaborate on environmental and

cultural compliance obligations in building in Hawai'i. We discuss the broad "lessons learned" along with the "lessons that were known but not fully learned/implemented". Finally, we discuss the project in the context of the evolving management oversight within the US (in particular under the NSF).

9911-22, Session 5

Multivariable parametric cost model for space and ground telescopes

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Parametric cost models can be used by designers and project managers to perform relative cost comparisons between major architectural cost drivers and allow high-level design trades; enable cost-benefit analysis for technology development investment; and, provide a basis for estimating total project cost between related concepts. This paper summarizes our ground and space telescope cost models. While space telescopes are 50X to 100X more expensive than ground telescopes, their respective scaling relationships are similar. An interesting speculation is that the role of technology development may be different between ground and space telescopes. For ground telescopes, the data indicates that technology development tends to reduce cost by approximately 50% every 20 years. But for space telescopes, there appears to be no such reduction because we do not re-fly similar systems. Thus, instead of reducing cost, 20 years of technology development may be required to enable a doubling of capability. Other findings include: mass should not be used to estimate cost; spacecraft and science instrument costs account for approximately 50% of total mission cost; and, integration and testing accounts for only about 10% of total mission cost.

9911-23, Session 5

The seven habits of highly effective project managers

Mark Warner, Richard T. Summers, National Solar Observatory (United States)

Why do some astronomy projects succeed, while others fail? There are obviously many different factors that can and do influence the outcome of any given project, but one of the most prevalent among successful projects is the combined skills and qualifications of the project manager (PM) at their helms. But this begs an obvious question: what exactly makes a project manager "skilled and qualified?" Asked another way, are there common traits, philosophies, and techniques that successful PMs share, and if so, what are they? The short answer is yes, the majority successful engineering project managers have significant things in common. The longer answer is there are at least seven of these key traits, or "habits" that many successful PM share and, more importantly, implement within their respective projects. This paper will present these seven key factors, including thoughts on scope and quality management, cost and schedule control, project team structures, risk management strategies, stakeholder management, and general project execution.

9911-27, Session 5

Agile software development in an earned value world: a survival guide

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Agile methodologies are current best practice in software development. They are favored for, among other reasons, preventing premature optimization by taking a somewhat short-term focus, and allowing frequent replans/reprioritizations of upcoming development work based on recent results and current backlog. At the same time, funding agencies prescribe earned value management accounting for large projects which, these days, inevitably include substantial software components. Earned Value approaches emphasize a more comprehensive and typically longer-range plan, and tend to characterize frequent replans and reprioritizations as indicative of problems. Here we describe the planning, execution and reporting framework used by the LSST Data Management team, that navigates these opposite tensions.

9911-20, Session 6

The LSST project execution plan for construction *(Invited Paper)*

Victor L. Krabbendam, LSST (United States)

The Large Synoptic Survey Telescope (LSST) Project is a public-private partnership that has entered full construction as a United States National Science Foundation (NSF) and Department of Energy (DOE) multi-agency project. The lead Federal Agency is the NSF which has approved construction under it Major Research Equipment for Federal Construction (MREFC) budget. The DOE Office of Science has taken the responsibility to build the LSST camera and has approved their element of the project as a Major Item of Equipment (MIE). The two federal agencies recognize the early investment of the LSST Corporation that provided significant initial funding from non-federal sources that directly supported design, fabrication of mirrors, and early site work. LSST has developed a unique Project Execution Plan to conduct the complex construction effort as a single project with a unique set of tools and processes to manage the effort, to support the necessary oversight, and to satisfy the reporting requirements for the multiple stakeholders. The plan includes earned value management for assessing progress against the plan, risk evaluation tools to guide the use of contingency resources for technical mitigations and opportunities, and extensive systems engineering tools to manage the technical configuration. The LSST management structure has been developed to addressed the scientific, engineering, and project challenges as well as the details of communication across a significantly distributed team. LSST is in full construction and scheduled for full science operation in 2022.

9911-24, Session 6

CARMENES: management of a schedule-driven project

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CARMENES (Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs) is a two high resolution (R~82,000) spectrographs covering simultaneously the visible (0.5 – 1.0μm) and near-IR (1.0 - 1.7μm) ranges and long-term stability to provide high-accuracy radial-velocity measurements (?1 m/s). CARMENES has been built for the 3.5m telescope at the Centro Astronómico Hipano-Alemán (CAHA), Calar Alto Observatory (Almería, Spain). CAHA is jointly operated by the Max-Planck-Society (MPG) and the Spanish National Research Council (CSIC). CARMENES was the initiative of a consortium of eleven German and Spanish institutions.

In February 2013, the project passed a Final Design Review. Six months later, the MPG and CSIC, the observatory's owners, made an independent evaluation concluding that CARMENES had to be ready for operations at the end of 2015. Since then, fulfilling the calendar was the driver of all project decisions. Moreover, the observatory's survival was linked to the instrument's success: should the instrument fail, the observatory would be closed. On the contrary, the instrument's success would give unique capabilities to the Observatory for Big Science. Such a challenge became to be our private Olympic Games: we had to be on time. This decision definitively impacted on the project dynamics, there was no room for a delay. The deadline, December 31st, 2015, was controlled by a strict tracking of the critical path; calendar deviations were corrected with risky decisions and fast tracking or even crashing methods were applied.

The management scenario was far from optimum. Most key people in the project shared their time with other duties; the observatory funding cuts; the tight budget, globally controlled by the project manager but distributed among the 11 partner centers with their own different rules, etc. Despite these difficulties, the close coordination among the project manager, the system engineer and the work package managers, the hard work of the whole team, and the support from the observatory were our best bets.

Two frenetic years after the calendar decision, we had manufactured, integrated and tested the two spectrographs and we were commissioning the instrument. The instrument first light took place on November, 9th, 2015. This paper describes the keys to success.

9911-25, Session 6

Management of the camera electronics programme for the World Space Observatory ultraviolet WUVS instrument

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World Space Observatory Ultra-Violet (WSO-UV) is a major international collaboration led by Russia, scheduled for launch in 2020. It will study the universe at ultra-violet wavelengths between 115 nm and 310 nm, exceeding the current capabilities of ground-based instruments. The WSO Ultra-Violet Spectrograph (WUVS) subsystem is led by a consortium of Russian institutes and consists of three spectrographs capable of high resolution spectroscopy (R>50,000) and long-slit low-level spectroscopy (R≈ 1,000).

RAL Space is contracted by e2v technologies Ltd to provide the CCD readout electronics for each of the three WUVS channels. The programme involves the design, manufacturing, assembly and testing of each Camera Electronics Box (CEB), it's associated Interconnection Module (ICM), Electrical Ground Support Equipment (EGSE) and harness.

An overview of the programme will be presented, from the initial design phase culminating in the development of an Engineering Model (EM) through qualification whereby an Engineering Qualification Model (EQM) will undergo environmental testing to characterize the performance of the CEB against the space environment, to the delivery of the Flight Models (FMs). The paper will discuss the challenges faced managing a large, dynamic project. This includes managing significant changes in fundamental requirements mid-programme as a result of external political issues which forced a complete re-design of an existing CEB with extensive space heritage but containing many ITAR controlled electronic components to a new, more efficient solution, free of ITAR controlled parts. The methodology and processes used to ensure the demanding schedule is maintained through each stage of the project will be presented including an insight into planning, decision-making, communication, risk management, and resource management; all essential to the continued success of the programme.

9911-26, Session 6

ALMA software releases versus quality management: and the winner is...

Erik Allaert, Moreno Pasquato, European Southern Observatory (Germany); Rubén Soto, ALMA (Chile)

The Atacama Large Millimetre /submillimetre Array (ALMA) consists of 66 high-precision radio-antennas, located on the Chajnantor plateau in the Chilean Andes, at an elevation of 5000 metres. Its construction and operation is a joint effort from partners on 3 different continents: the European Southern Observatory (ESO), the U.S. National Science Foundation (NSF) and the National Institutes of Natural Sciences (NINS) of Japan. The development of the software to operate this sophisticated array, acquire, monitor and evaluate scientific data is equally distributed over these 3 continents, involving many institutes and software engineers.

The ALMA Observatory was inaugurated in March 2013, and the construction phase has formally been completed, but the software development effort continues at roughly the same level as during construction, to cope with the capabilities offered to the scientific community in the context of ALMA's yearly Observing Cycles. This implies that in the course of a year several software releases have to be prepared, dealing with everything from proposal preparation and submission software up to the deployment of the online software commanding the array at the official start of a new cycle at the observatory. These software releases follow a pre-defined process; there are several quality aspects followed up continuously as part of this process, providing a quality status overview to the developers, end-users (scientists and engineers), plus the Release and Acceptance Managers. The corresponding report assessing the software quality of a new release is submitted to the Acceptance Review.

As the ALMA observatory is fully operational, it is used on a daily basis to produce scientific data for the approved projects, and also by engineering teams to extend existing capabilities or to diagnose and fix problems. Hence the preparation of new software releases up to their deployment is "just one more activity", competing for resources with all other activities. Testing a new release and ensuring its quality is acceptable to the observatory is of course fundamental, but can on the other hand not monopolize the observatory's resources or jeopardize its commitments to the scientific community, such as publicly announced milestones for the start of new observation cycles.

In this paper we describe the tools and metrics used so far to monitor the quality of ALMA software releases, and the results this has produced. After having applied this for a number of releases, we have also identified several areas within the release or acceptance process where improvement is desired or needed, and where the stumbling blocks are.

9911-28, Session 6

Project management of DAG: Eastern Anatolia Observatory

Onur Keskin, Isik Üniv. (Turkey); Lorenzo Zago, HEIG-VD (Switzerland); Cahity Yesilyaprak, Atatürk Üniv. (Turkey); Sinan K. Yerli, Middle East Technical Univ. (Turkey)

The four meter DAG (Eastern Anatolia Observatory in Turkish) telescope is not only the largest telescope in Turkey but also the most promising telescope in the northern hemisphere with a potential to offer scientific observations with its cutting edge technology. DAG is designed to be an AO telescope which will allow both infrared and visible observations with its two Nasmyth platforms dedicated to next generation focal plane instruments. In his paper, status updates from DAG telescope will be presented in terms of; (i) in house optical design of DAG, (ii) tender process of telescope, (iii) tender process of enclosure, and (iv) tender process of the observatory building. Also status updates from the focal plane instruments project and possible collaboration activities will be presented.

9911-29, Session 7

Managing engineering in a science project: lessons for SKA from MeerKAT *(Invited Paper)*

François Kapp, SKA South Africa (South Africa)

The SKA is a large science project - planning to commence construction after 2018 - to construct the world's largest Radio Telescope. MeerKAT is one of the precursor projects to the SKA, based on the same site that will house the SKA Mid array in the arid central Karoo area of South Africa. Taking the perspective of signal processing hardware development, we analyse the challenges that MeerKAT encountered and extrapolate them to SKA in order to prepare the System Engineering and Project Management methods that could contribute to a successful completion of SKA.

Using the MeerKAT Digitiser, Correlator/Beamformer and Time and Frequency Reference Systems as an example, we will trace the risk profile and engineering approaches of these systems over time and show the effects of varying levels of System Engineering rigour on the evolution of their risk profiles. It will be shown that the most rigorous application of System Engineering discipline resulted in the most substantial reduction in risk over time.

At the start of the MeerKAT project, the Digitiser was the only of the three systems under consideration was a first-of-kind development, and, as a result, it dominated the MeerKAT risk registers. It was also a driver of the project critical path. As an engineering response, the team used rigorous System Engineering processes and principles in order to manage the risks - both technical and schedule. These processes were implemented early in the project and in spite of the perceived impacts on schedule. Over time, the Digitiser has reduced in significance as a contributor to the technical risk profile of the MeerKAT telescope. It is in full production and not on the critical path of the higher level system.

Since the challenges faced by SKA are not limited to that of MeerKAT, we also look into how that translates to a system development where there is substantial complexity in both the created system as well as the creating system. Since the SKA will be designed and constructed by consortia made up from the ten member countries, there are many additional complexities to the organisation creating the system - a factor that MeerKAT did not face. Factors outside of engineering, for instance procurement models and political interests, also play a more significant role, and add to the project risks of SKA when compared to MeerKAT.

9911-30, Session 7

Gemini Observatory base facility operations: systems engineering process and lessons learned

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The Gemini Observatory Base Facility Operations (BFO) project began in 2013, with the goal of having both telescopes operating from their respective sea level base facilities by the end of 2015. Due to resource constraints, it was decided that Gemini North BFO would be implemented first, as it would generate the most cost savings and user benefits due to the more harsh operating environment of Maunakea. Gemini South (Cerro Pachon, Chile) BFO implementation will follow in 2016.

Gemini North Observatory successfully began nighttime remote operations from the Hilo Base Facility control room in November 2015. As this project was a major observatory-wide undertaking, the implementation of GN BFO was a great learning experience for many of our employees, especially the author of this paper, the BFO Systems Engineer.

In this paper I discuss the key factors that led to the successful implementation of the GN BFO project, the tailored Systems Engineering processes used for the project, the various software tools used in both project management and systems engineering support, and finally discuss the lessons learned from the Project Management team.

The GN BFO project was challenging both in terms of technical and managerial complexity and also at the human level, as it represented a major change to the routine of the Gemini operations. The GN BFO project was separated into 17 individual Work Packages of varying degree of technical complexity. As there was only a single dedicated Systems Engineer to the project, this necessitated a tailored systems engineering approach at both the project top-level and on an individual Work Package level. The less complex work packages received little to no systems engineering involvement, while the more complex work packages (in terms of their technical complexity and level of interfacing with existing observatory systems) required a much more rigorous systems engineering approach.

The Project Management team identified early on that because this project covered many areas of the Observatory, it meant it involved people from many backgrounds and expertises. Therefore we made a decision early on that any software tools used during the project would be simple enough that everyone could use. As a result several software tools were used for requirements management, tracking Work Package progress, risk identification, tracking and mitigation, project level and Work Package issue tracking, and finally for change management. Some of these tools overlapped in their functionality and became too cumbersome to manage, while others were modified from their initial purpose and successfully met our needs.

Both the tailoring of the level of systems engineering involvement at the individual work package level and the tools used yielded many important lessons learned, that will no doubt aid us in our Gemini South BFO implementation in 2016, as well as in future technical projects at Gemini Observatory.

This paper will focus on the Systems Engineering practices and processes used during the lifecycle of the Gemini North BFO project, and how those practices and processes will be further tailored based on the experience and lessons learned, for the upcoming Gemini South BFO project.

9911-32, Session 7

European Extremely Large Telescope (E-ELT) availability stochastic model: integrating FMEA, influence diagram, and Bayesian network together

Gianluca Verzichelli, European Southern Observatory (Germany)

The paper presents the description and use of a Telescope Availability Stochastic Model developed in the GeNIE environment based on SMILE (Genie has been developed at the Decision Systems Laboratory, University of Pittsburgh).

The E-ELT will be the largest optical/near-infrared telescope in the world. Its design comprises an Alt-Azimuth mount reflecting telescope with a 39-metre-diameter segmented primary mirror, a 4-metre-diameter secondary mirror, a 3.75-metre-diameter tertiary mirror, adaptive optics and multiple instruments.

The model is used for several purposes depending on the development stages of the Programme. In the early phases of the development it is used to define quantitative achievable and cost effective availability, reliability and maintainability (RAM) requirements for the procurement of Sub-systems and for availability budget definition as well for evaluating "what-if" scenarios.

Later on it is adopted as a framework where - as soon as new information related to Contractor's detailed design solutions is provided - it is embedded and a refined assessment of the Telescope Availability can be made.

Furthermore, when first reliability and maintainability data become available, either from a Highly Accelerated Life Test (HALT) campaign or from field data, the adoption of Bayesian Network allows updating the prior distributions with posterior distributions and thus re-compute the overall Telescope Availability.

The major points to be covered in the paper include:

• Introduction of the European Extremely Large Telescope

- Key reliability, availability and maintainability (RAM) Observatory Top Level Requirements

- Overview of Telescope Procurement and Design & Development Business Models

- Definition and Verification of RAM Requirements in a Contractual Framework

- Highlights of Telescope Operations and Maintenance Activities

• Definition of Failures and Faults

• Overview of different types of Availability

- Inherent, Operational and Achieved Availability

- Availability is not Reliability...

- Implications on Telescope Acquisition vs Ownership Costs

• Introduction of Degradation-Based Reliability

• Model Description

- Telescope Product Breakdown Structure

- Overview of the RAM items considered in the Model: Operating Time, Standby Time, Administrative and Logistics Down Time (ALDT) and Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), etc.

- Modular Approach Development

- Introduction of FMEA elements and Degradation-Based Reliability

• Model Results

- E-ELT Availability Results

• Model Use

- Availability Apportionment Verification

- Prior and Posterior Distributions Updating

- Telescope Master Minimum Equipment List Definition (T-MMEL) Definition

- Telescope Failure, Detection, Isolation and Recovery (FDIR) Control Strategy Definition

• Possible Further Development

• Conclusions

The paper has highlighted the key features of the E-ELT Telescope Availability Stochastic Model. It has outlined the various steps and assumptions that have been used for developing the model. It has demonstrated how the use of such model may reduce the risk of introducing unrealistic or non-cost effective reliability, availability and maintainability requirements into specifications for the definition of the System and procurement of Sub-systems. Finally it has shown how the information and knowledge contained in the model may be seamlessly reused for the definition of the Telescope Master Minimum Equipment List (T-MMEL) and the Telescope Failure, Detection, Isolation and Recovery (FDIR) Control Strategy.

9911-33, Session 7

Considerations regarding system engineering in large scale projects with heterogeneous contexts

Andrea Cremonini, Maria Grazia Labate, Marco Caiazzo, Rodrigo A. Oulgin, Juande Santander-Vela, Tim Stevenson, SKA Organisation (United Kingdom)

With This paper I would like to share some considerations and lessons learned based on my direct experience as system engineer at the SKA project. This is a very wide and ambitious program, which involves several stakeholders, heterogeneous as cultural background, technological heritages, disciplines, motivations and competences as never before. My role is to amalgamate efforts in order to deliver the "MID telescope" and often I discovered that, "system engineering", assume a wider meaning than purely being a disciplined sets of processes

9911-34, Session 7

GESE mission concept optimization

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Here we describe the work and results of a study that we have undertaken to optimize the mission concept for the Galaxy Evolution Spectroscopic Explorer (GESE) space telescope. We define mission concept optimization as the development of a combination of science return and overall mission cost that has the highest probability of successful implementation. We approach this optimization by inserting a specification for "quantitative measurement capabilities" between the two conventional mission definition phases of: 1) establishing science requirements; and 2) developing a mission concept to achieve that science. Examples of quantitative measurement capabilities include characterizations of measurement range and resolution in the spectral, temporal, intensity, and spatial/angular domains that are required to achieve science objectives but are independent of instrument and mission design. Separating the science and engineering phases in this manner facilitates the use of automated engineering tools to efficiently estimate the direct and indirect costs of design options such as instrument collecting area, mission orbit, and mission duration. This separation also simplifies the process of down- (or up-) scoping science and measurement requirements to obtain an implementable combination of science return and mission cost.

9911-51, Session PSMon

Dynamical compensation for the optical aberrations from a telescope with a large-single-piece primary mirror: modeling and control of the dynamical systems for its active optics, supporting and positioning

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This paper describes a mathematical model for the optics and supporting systems which has been gotten from the basic design of the new San Pedro Mártir optical telescope which is going to be developed by UNAM, INAOE and CIDESI in collaboration with others international institutions.

These model considers both static and dynamic states of the entire opto-mechatronic system of the telescope, because its intention is to work as reference for the detailed design of the robotics for the supporting and positioning of the optical system.

The mathematical model output is the wavefront at the image plane, which is simulated to analyze aberrations and compensate them through the robotic support and the active optics of the primary mirror.

Simulations of the entire system have solved by commercial programs but the algorithm has been developed based into the spatial and dynamic response of the opto-mechatronics system, by considering the fundamental equations for optics, mechanical vibrations, kinematics and mechanisms dynamics.

The algorithm developed solves the mathematical equations of the physics involved, but it starts from a multi-variable linear model raised like a dynamic state space, then it is discretized and it is converted in a finite element model with dynamical border conditions.

All solver algorithm is described and some recommendations for the telescope design are done considering the simulations results.

9911-52, Session PSMon

Using integrated multi-body systems for dynamical-optical simulations

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In order to investigate and analyse the dynamical-optical behavior of high precision optics, integrated modeling strategies and methods are proposed. For instance, this optical systems can be an astronomical telescope or a lithographic objective. In order to derive a simplified mechanical model for time simulations with low computational cost, the method of elastic multibody systems in combination with model order reduction methods is used. Mechanical and optical simulation models are derived and implemented. In order to clarify these methods, an academic mirror example is chosen.

Ground-based telescopes are highly resoluting optical systems consisting of precise mirrors. They are accurately mounted and they are very sensitive with respect to vibrations. During the observation time, small mechanical vibrations can be sufficient to produce inacceptably aberrated images. Even the adaptive optical unit or other motion systems can unintentionally excite the whole construction. The mechanical behavior of such optical systems can be described by a combination of rigid body motions and small deformations.

The mechanical model is based on elastic multibody systems with the floating frame of reference. In contrast to a detailed and large global model based on the finite element method, a reduced and modular elastic multibody system leads to low computational effort for simulations in the time domain. Furthermore, the system can be analysed and assembled step by step and it is able to include only the relevant dynamical behaviour due to appropriate model order reduction methods. For sequential ray tracing through several lenses and mirrors during the optical simulation, a continuous description of the mechanically deformed surfaces is required. Thereby, the line of sight describes the displacement of the center of intensity and the wavefront aberrations characterise the blurring and image quality. In order to take also wave optical effects during an image simulation into account, Fourier optical methods are utilized.

The influence of different model order reduction methods will be presented and analysed for an exemplary integrated model. It is based on an annular lightweight mirror with a parabolic shape made of aluminum. Here, the influence of the model order reduction methods is analysed and the mechanical-optical transfer behaviors of different wavefront aberrations are investigated. It is shown, that the mechanical-optical sensitivities depend on the frequency of excitation. Moreover it is investigated, whether the sensitivities can be used during the model order reduction in order to describe the overall behavior with an optimized model. Finally, the performance of different simulation strategies is assessed and the application limits are identified.

9911-53, Session PSMon

A feasibility study for conducting unattended nighttime operations at Keck Observatory

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In 2015, W. M. Keck Observatory conducted a feasibility study for conducting nighttime operations on Maunakea without any staff on the mountain. The study was motivated by the possibility of long term operational costs savings as well as other expected benefits. The goals of the study were to understand the technical feasibility and risk as well as to provide labor and cost estimates for implementation. The results of the study would be used to inform a decision about whether or not to initiate a project aimed at the development of this new unattended nighttime operating mode. In this paper we will describe the study process as well as a brief summary of the results including the identified viable design alternatives, the risk analysis, and expected scope of work. We will also share the decisions made as a result of the study and the current status of related follow-on activity.

9911-54, Session PSMon

STABLE: fine pointing control approach for image stabilization of balloon-borne telescopes

Carl R. Seubert, Milan Mandic, Herrick Chang, Jet Propulsion Lab. (United States)

The Astro2010 decadal survey places the study of dark matter and the accelerating expansion of the Universe at the top of its priorities for the next decade. At the same time, NASA strategic goals also focus on studies of the chemical composition of galaxies as well as the race to find Earths exoplanet counterpart. For these scientific objectives, a common requirement is an ultra-stable pointing system (sub-arcsecond) for long exposure imaging supported by space and ground based telescopes. A promising alternative is to use high altitude balloons as a telescope observation platform.

High altitude balloons enable two key advantages over conventional observatories: 1) they raise the telescope above more than 99% of the Earth's atmosphere which significantly reduces atmospheric seeing and 2) they avoid the high cost of space observatories by avoiding the expensive spacecraft development and launch services. However, one of the major technical challenges to perform scientific observations is precision pointing.

This paper describes the design of fine pointing control system as a balloon-borne payload for precision pointing observations. This fine pointing architecture used in combination with a balloon-borne coarse pointing gimbal stage can provide sub-arcsecond focal-plane image precision. This is achieved over a 60 second exposure time, while targeting relatively dim stars of magnitudes 10-12.

The foundation of the fine pointing architecture is based on two sensors; a focal plane image camera sampled at 50 Hz, and a Dynapak 14 triaxial attitude rate sensor (ARS). The high-rate ARS measures ultra-low level angular jitter in the sub-microradian regime, with low noise equivalent angles and large integration bandwidth. The actuation is done by a PI S-330 fast steering mirror (FSM), sampled at 1000 Hz, and featuring custom, low-noise strain gauge sensing electronics. The fine pointing control architecture blends these pieces together with image-based measurements in feedback and ARS measurements in feedforward to expand the measurement bandwidth from 0-200 Hz. This sensing bandwidth allows control bandwidth beyond 35 Hz with significant disturbance attenuation in lower frequencies, to capture typical balloon platform disturbances, such as azimuth reaction wheels.

The control design follows strict design principles, maintaining system stability with healthy gain and phase margins. In addition, this paper will cover the development of auxiliary algorithms, for processing ARS measurements, which is necessary when using ARS in feedforward, as well as for computing the centroid value of the target star on the camera focal plane array.

Extensive analysis and expected flight performance of the system is presented. While the fine pointing control architecture is decoupled from the balloon coarse pointing stage (making it a generic payload viable for balloon telescope systems), a representative coarse loop is simulated using previous balloon flight data. Results of high fidelity simulations show performance to better than 100 milliarcsecond RMS in 2 axes. This is achieved while using lab tested performance data of the sensors and actuators. In addition, preliminary results from limited closed loop tests performed within the lab environment are also presented.

9911-55, Session PSMon

Requirements management at Gemini Observatory: a small organization with big development projects

Madeline Close, Gemini Observatory (United States)

Gemini Observatory is continuously engaged in development projects to enhance scientific capabilities and improve operational efficiency. Historically, these development projects have been supported by a very limited systems engineering infrastructure. In seeking to mature this infrastructure, the Gemini Systems Engineering Group started studying requirements management. The team identified several steps necessary to implement requirements management: role definition, process definition, requirement data definition, change control definition, and finally tool selection. In this paper, these five steps will be presented and expanded upon, with reference to the team's personal experience in selecting and configuring a dedicated requirements management tool. Key activities are described for each step, and guidance on tailoring each step to the particular project characteristics (size, internal or external, etc.) is provided. The paper will also address requirements reuse across multiple projects and the implications for requirements management.

9911-56, Session PSMon

AST3-3 IR camera for the Kunlun infrared sky survey (KISS): thermal optimization and system performance

Jessica R. Zheng, Jonathan S. Lawrence, Robert Content, Vladimir Churilov, Australian Astronomical Observatory (Australia); KaiYuan Zhang, Xiangyan Yuan, Haiping Lu, Nanjing Institute of Astronomical Optics & Technology (China)

AST3-3 IR camera is designed for the Kunlun Infrared Sky Survey (KISS) with an infrared camera for the AST3-3 wide field telescope; it will provide the comprehensive exploration of the time varying Universe in the infrared and is going to be located at Kunlun Station (Dome A), Antarctic plateau, one of the most unique low sky background in K-dark band (2.4μm). KISS is the first deep and wide K dark survey, a path finder for future.

In this paper, we present that the thermal optimization design and system performance evaluation for the KISS infrared camera design. To take full advantage the unique low sky background at Dome A, the thermal emission from telescope and IR camera needs to be carefully investigated. We examined different IR camera design options by using different thermal control methods by either adding narcissus mirror or controlling pad behind telescope secondary mirror. It becomes clear that full cold-stop within the camera is a feasible, less risk and economical solution for this kind of survey telescope.

After the design of IR camera is decided, we setup the full thermal analysis model for the camera optimization with commercial software FRED. Since the sky emission becomes very low comparing to temperate site, it becomes necessary to examine thermal self-emission from telescope and its instrument carefully as they could emit prodigiously in the infrared. The major sources of the background radiation against the faint astronomical sources are black-body thermal emissions from the atmosphere and the telescope. They are mostly composed of atmospheric emissivity, emission of telescope mirrors and structure in beam, warm windows and surfaces within the cryostat and scattered light within instrument.

Using FRED, we are able to calculate the solid angle from all critical and illuminated objects; hence the thermal emission from all structures can be calculated at different ambient temperature. The size of the cold stop and temperature of the camera body are therefore optimized respectively. Different emissivity of black surfaces with different methods is compared and it is found that Acktar vacuum black can be used for all camera body internal mechanical surfaces which provide good thermal and low outgas performance. We also examine the PST (Point source transmission) of the system by using scattered light model and found that we can obtain the 10^3 suppression of scattering light within the telescope field of view.

To evaluate the system performance, a telescope exposure time calculator is setup in which the signal to noise ratio for an observed astronomical object is calculated based on sky transmission, spectral responses of different components and thermal emission from telescope and instrument at different ambient temperature. It is found that the IR camera can achieve 18.5 mag at K dark band at 235K with 25s exposure time for 1? operation, for 10 ? with exposure time of 1 hour, it can go up to 18.7mag which meets the system design requirements.

9911-57, Session PSMon

Using tailored methodical approaches to achieve optimal science outcomes

Lory Mitchell Wingate, National Radio Astronomy Observatory (United States)

Project management is an effective and widely adopted methodology used to control cost, schedule, and scope for a specific activity. The successful use of project management in manufacturing and production has been shown to provide such a competitive advantage that the discipline has spread to use in other parts of the lifecycle such as research and development, and more recently into operations management.

Systems engineering is a standardized, disciplined process with a mission to ensure that the outcomes of a project match the intent of the customer, or if they diverge in any way, that the changes are understood, captured, and controlled from both the component and the systems perspectives. The role of Systems Engineering is to provide a comprehensive view of how all the pieces fit together, to ensure that each piece actually works as specified as a unique component, and as an integral part of the system as a whole.

Systems engineering complements project management in that it assumes direct responsibility for the development and control of some activities for which the project manager is also responsible, but at a much deeper level. Systems engineering provides a management service to the project manager ensuring that the project comes together as a whole. And it provides a technical service to the project manager to ensure that the design, development, production, or other technical project activities meet specifications and ultimately worked as planned. The technical processes used by systems engineers include modeling and simulation, which help establish measureable parameters for the requirement(s) and often also provide performance specifications. This is imperative for science projects that may start out with vague high-level science requirements. In situations where choices among technology could be adopted, these activities also help clarify the costs, benefits and constraints of each proposed solution.

Within the scientific realm, these disciplines provide structure to help define and carefully control the evolution of requirements so that science outcomes can be optimized within the costs and schedule provided by the customer. An *appropriate application* of these disciplines can be the foundation upon which success in scientific endeavors can be achieved. Both project management and systems engineering disciplines require tailoring to fit the project and to ensure that the appropriate level or rigor is applied; that the right amount of each discipline is applied to the project so that it is not be burdened, yet helps optimize the project performance. For standard projects (which fit all the traditional project management criteria such as a defined schedule, budget, and scope), tailoring involves consideration of the entire framework, and then scaling the framework down to fit project needs. For scientific research and development projects, tailoring generally involve a progressively increasing application of these processes.

This presentation provides insights into the challenges, lessons learned, and potential applications associated with applying project management and systems engineering disciplines onto scientific research and development projects in order to increase the potential for achieving optimal science results.

9911-58, Session PSMon

SALT tracker upgrade utilizing aerospace processes and procedures

Raoul van den Berg, Southern African Large Telescope (South Africa); Chris Coetzee, South African Astronomical Observatory (South Africa); Ockert Strydom, Janus Brink, Keith R. J. Browne, Eben P. Wiid, Wouter Lochner, Grant Nelson, Paul Rabe, Martin Wilkinson, Vic Moore, Adelaide Malan, Southern African Large Telescope (South Africa); Jonathan Love, South African Astronomical Observatory (South Africa); Anthony R. Koeslag, Southern African Large Telescope (South Africa)

The SALT Tracker was originally designed to carry a payload of approximately 1000 kg. The current loading exceeds 1300 kg and more instrumentation, for example, the Near-Infrared (NIR) arm of the Robert Stobie Spectrograph (RSS), is being designed for the telescope. In general, provision also had to be made to expand the envelope of the tracker payload carrying capacity for future growth as some of the systems on SALT are currently running with small safety margins.

As part of the RSS-NIR development project it was decided to upgrade the SALT Tracker to be able to carry a payload of 1875 kg.

A pre-project study showed that in order for the SALT Tracker to carry this higher payload, a number of upgrades are required on the sub-systems of SALT. These were defined as three Project Stages called Y-Upgrade, Rho-Upgrade and Hexapod-Upgrade, respectively.

Before the project “Kick-Off” it became evident that neither SALT nor SAAO had the required standard of processes and procedures to execute a project of this nature. The Project Management, Mechanical Design and Review processes and procedures were adopted from the Aerospace Industry and tailored for our application. After training the project team in the application of these processes/procedures and gaining their commitment, the Tracker Upgrade Project was “Kicked-Off” in early May 2013.

It was clear during the first stage of the project that the learning curve for the project team to adapt to these new processes and procedures was steep, but they coped extremely well. By the second stage of the project the team started seeing the benefits of executing a design and development project in a more structured and organised manner. Today, even new projects on SALT bear testimony to the benefits of following these processes and procedures.

The application of these aerospace-derived processes and procedures, as used during the Tracker Upgrade Project, were very successful in that:

1. It ensured the generation and quality of complete/configured/traceable engineering and manufacturing data packs.

2. All designs of systems and sub-systems have been extensively tested and found to have met, or in some cases even exceed, the requirements and specifications.

3. The Y-Upgrade system has been installed on SALT and is operating successfully.

4. The technical and project risks have been reduced to acceptable levels with mitigation plans in place during the execution of the project.

5. After 32 months the Tracker Upgrade Project is still within budget and only 3% behind schedule.

Truly remarkable achievements for such a design and development project.

In this paper the authors highlight some of the details of the implemented processes and procedures as well as specific challenges that needed to be met while executing a project of this nature and technical complexity. All while remaining within a limited budget and schedule.

9911-59, Session PSMon

PSF simulations as part of the on-ground calibration of the NISP infrared spectrometer instrument for Euclid

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EUCLID is a telescope dedicated to the understanding of the acceleration of the expansion of the Universe with the measure of large surveys of the sky in the visible and near infrared ranges. Its payload is composed of a 1.2 m aperture telescope with two instruments: a visual imager (VIS) and a near-infrared spectrometer and photometer (NISP). The NISP integration is under LAM responsibility and the CPPM is in charge of the reception, integration and individual characterization of all detectors. One of the main objectives of the test campaign is the on-ground calibration of the NISP which is also a responsibility of these laboratories.

The test campaign will regroup functional tests of the payload, performance tests of the instrument, calibration procedure validation and observation scenario tests, all done at LAM.

A specific GSE will be used to simulate the telescope (VGS) and will be put in front of the NISP. This VGS will produce measured PSFs during the test campaign. The campaign includes in particular a precise determination of the focus position of the NISP instrument with respect to the EUCLID object plane.

In order to prepare this test, a tolerance model (Zemax) including the NISP and the VGS contributions will be developed, adjusting focal length, to generate a PSF database. This database will allow to develop the test procedure, based on simulated PSFs, and related analysis tools for the test ground campaign and will be further used to validate the calibration procedure verification. This simulated PSF database will be also used in pixel simulation to evaluate the performance of the instrument up to the science level.

After a description of the main objectives of the NISP calibration, we will focus on the method developed to realize and validate the NISP focus test, based on PSF simulations i.e.:

• Method to fit the PSF on the basis of the Markov Chain Monte Carlo (MCMC) method, or to be more specific, on the slice sampling method;

• Establishment of a PSF database base on a Zemax model;

• Procedure to minimize the PSF for a test of the focus.

9911-61, Session PSMon

Problem reporting and tracking system: a systems engineering challenge

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In the ALMA observatory, in average, are reported 12 unexpected problems daily, which can affect the observations, software, planned maintenance, infrastructure, instrumentation, equipment or any other operational component. These problems are generated and managed by different groups, with dissimilar backgrounds and some cases different locations around the world. The tracking of these problems becomes in a very interesting challenge, at the moment to address them and applying a systemic view.

The problem reporting and tracking system (PRTS) is the ALMA system based in JIRA to register and track all problems and investigations arisen in operation. In the JIRA project PRTSPR are created the tickets of problems, where it is included all information available about them, such as: the event times of the failure and the system overview at the moment when the failure happened. On the other hand, the investigations are tracked separately, in another JIRA project PRTSIR, where are included all outcomes of the analyses carried out to determine the root causes, the affected components, the verification and validation of the solutions implemented.

At the end of 2014 the number of PRTSIR tickets unresolved assigned to the ALMA department of engineering (ADE) was more than 800, number extremely large to get a proper tracking considering the size of the ADE staff. In this work, we shall present a set of concrete actions applied at the basis of understanding the complexity of the problem, which finally got to improve the interactions between different subsystems and enhance the communication at different levels. Currently, the number of ticket unresolved has been considerably decreased and the tracking of the problems has presented clear improvements among the groups. Even so, there are a lot of challenges to be addressed and enhancements to be applied, in order to have a robust and functional PRTS that ALMA needs.

9911-62, Session PSMon

Daniel K. Inouye Solar Telescope: computational fluid dynamics analysis and evaluation of the air knife model

Isaac McQuillen, LeEllen Phelps, Mark Warner, Robert P. Hubbard, National Solar Observatory (United States)

Implementation of an air curtain at the thermal boundary between conditioned and ambient spaces allows for observation over wavelength ranges not practical when using optical glass as a window. The air knife model of the DKIST project, a 4-meter solar observatory that will be built on Haleakala, Hawaii, deploys such an air curtain while also supplying ventilation through the ceiling of the coudè lab. The findings of CFD analysis and subsequent changes to the air knife model are presented. Major design constraints include adherence to the Interface Control Document (ICD), separation of ambient and conditioned air, unidirectional outflow into the coudè lab, integration of a deployable glass window, and maintenance and accessibility requirements. Optimized design of the air knife successfully holds full 12 Pa back pressure under temperature gradients of up to 20 °C while maintaining unidirectional outflow. This is a significant improvement upon the .25 Pa pressure differential that the initial configuration, tested by Phelps, indicated the curtain could hold. CFD post-processing, developed by Vogiatzis, is validated against interferometry results of initial air knife seeing evaluation, performed by Hubbard. This is done by developing a CFD simulation of the initial experiment and using Vogiatzis' method to calculate error introduced along the optical path. A Kolmogorov model is applied in order to convert from seeing in arc seconds to rms wavefront error in nm and thus obtain congruity between units in the CFD model and units in the initial experiment. Seeing error, for both temperature differentials tested in the initial experiment, match well with seeing results obtained from the CFD analysis and thus validate the post-processing model. Application of this model to the realizable Air Knife assembly yield seeing errors that are well within the error budget under which the air knife interface falls, even with a temperature differential of 20 °C between lab and ambient spaces. With ambient temperature set to 0 °C and conditioned temperature set to 20 °C, representing the worst-case temperature gradient, the phase analog to the OPD-based rms wavefront error in units of wavelength is 0.0774 (38.7 nm at ? = 500 nm).

9911-63, Session PSMon

Conceptual design of the TMT instruments cryogenic cooling system

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In order to ensure that the Thirty Meter Telescope (TMT) will achieve the expected image quality and detection ability for adaptive optics assisted observation, it is essential that mechanical vibration from all sources in the observatory be minimized. This includes the cryogenic cooling systems used to maintain near infra-red and visible science detectors, and other components contained in vacuum dewars, at temperatures as low as 70 K.

Recently, a conceptual design of a facility cryogenic cooling system for the TMT observatory has been developed by the Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences (TIPC, CAS). This novel design approach is based upon the Brayton cycle which has the characteristics of long life, wide temperature range, large cooling capacity and low vibration. This cryogenic cooling system consists of two warm compressors, two cold boxes, three cryogenic valve boxes, warm transfer lines and vacuum jacketed cryogenic transfer lines. In this system, pressurized room temperature helium is delivered to the heat exchangers

and turbine expanders located in the cold boxes on the Nasmyth platforms. And the cold helium gas is then distributed to each instrument via the cryogenic valve boxes. This cryogenic system design produces 2.9 kW of cooling power at 65K and 0.4 kW of cooling power at 160 K. This paper presents the results of trade studies, process design, system layout, cooling power, operating modes and reliability estimates.

9911-64, Session PSMon

Dynamic position accuracy analysis of fiber positioner

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The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) is a special quasi-meridian reflecting Schmidt telescope installed with 4000 optical fibers, which require precise alignment with the celestial target during the astronomical observation. Therefore, the fiber positioning system is the key to ensure effective observations. In order to reduce the loss of the coupling efficiency due to the misalignment between a target and a fiber, the fiber must be positioned within 40?m of the target. For the purpose of improving the positioning accuracy of fiber ends, it is essential in both theory aspect and practical aspect to study the sources and compensation method of the positioning error. In this paper, the sources of the positioning error, including dimensional deviation and joint clearance, are taken into consideration, and the corresponding error model is established respectively. The influences of different error sources are analyzed through appropriate simulation method. First, the model of positioning error caused by dimensional deviations is established based on the vector chain analysis method, and the numerical solution of the model is obtained through Monte Carlo numerical simulation method. Second, two virtual prototype models of fiber positioner, one of which contains joint clearance while the other one is zero-clearance, are built on multi-body dynamics simulation program ADAMS. Positioning error of fiber positioner caused by joint clearance is obtained by comparing the computational results of the two different models. Finally, the comprehensive positioning error is derived by coupling the two errors caused by dimensional deviations and joint clearances. Precise position measurement experiments of fiber ends are conducted , then a comparison is made between experimental and theoretical analysis to confirm the rationality of simulation models. Some conclusion is obtained, which can avail in further study.

9911-65, Session PSMon

Development of the space telescope mirror construction

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Nowadays mapping is an important task in the everyday and military purposes, performs a quick update and supply of high-quality images with the help of space telescopes. The better the image quality, the larger the telescope in size, and therefore require more capacity and investments to launch these telescopes into orbit. Because of this reasons there are happens works of making components of the telescope easier in mass.

The purpose of this paper is to find the most optimal design of the main mirror of a space telescope with preassigned characteristics and for a known material. The optimal design implies a set of minimum mass and maximum rigidity. The scheme to facilitate mirrors: edge-ring.

We study the dependence of the values ??of displacements [m] and static stress [N / m2] in the mirror of the different configurations of edge-ring design, different kinds and value of load on mirror: it must be resistant not only to its weight on the Earth, but also to forces appeared at the moment of rocket start.

From the totality of the results will be made conclusions of the optimal design of the primary mirror of the telescope with the specified parameters.

9911-66, Session PSMon

Meeting the challenges of bringing new base facility operation model to Gemini Observatory

Atsuko Nitta, Gemini Observatory (United States); Gustavo Arriagada, Gemini Observatory (Chile); Andrew J. Adamson, Scot J. Kleinman, Gemini Observatory (United States)

The aim of the Gemini Base Facilities Project is to provide the capabilities to perform routine night time operations with both telescopes and their instruments from their respective base facilities with no one at the summit. Tightening budget constraints prompted this as both a mean to save money and an opportunity to move toward increasing remote operations in the future.

Key challenges included: (1) Managing parallel work within the project while sharing resources with opeartions. (2) Testing commissioning and introducing new tools to operational systems without adding significant disruptions. (3) Staff buy-in to the new operational model given their involvement as both labor resources and users. There were two principles we applied to overcome these challenges and successfully complete the project ahead of schedule at Gemini North "Bare Minimum" and "Gradual Descent" I will discuss how we managed the cultural and human aspects of the project through these concepts. The other management aspects will be presented by Gustavo Arriagada, the Project Manager.

9911-67, Session PSMon

Application of the ALMA Observatory experience with software engineering tools to the system engineering design process for SKA

Rodrigo A. Olguin, SKA Organisation (United Kingdom); Tzu-Chiang Shen, ALMA (Chile)

The Software Group of the ALMA Observatory during the construction stage implemented a set of tools belonging to the discipline of Software Engineering with aim of successfully managing the complexities and problems proper of a large system as ALMA which is currently the world's largest radio telescope in operation.

The SKA Observatory, actually in the pre construction phase, is being designed following a tailored Systems Engineering approach. The design process is being carried out by more than 300 people conforming 7 design consortia and the SKA Organisation. The complexities in the design coming from the ambitious science goals and integrating such a large organisation sets not only technical, but also organisational and information sharing challenges. It is envisioned to learn from the ALMA experience with Software Engineering tools to explore and develop a plan to apply them in the SKA system engineering process aiming to mitigate the different design process risks. A set of potential implementations for SKA will be presented.

9911-68, Session PSMon

The use of information technology tools in the system engineering design process of SKA

Rodrigo A. Olguin, Juande Santander-Vela, Andrea Cremonini, Maria Grazia Labate, Marco Caiazzo, Daniel Hayden, Susan Nel, SKA Organisation (United Kingdom)

The SKA Observatory, presently in the Pre-Construction phase, is being designed following a tailored Systems Engineering approach. Large-scale engineering design projects are characterised by an equally large set of documentation and a complex configuration management structure, with design resources also spread across more than 10 different countries. SKA is innovating the way that astronomy projects are designed by making use of the new generation of Information Technologies to manage the System Engineering and design processes. SKA is hosting services for requirements management (JAMA), Model-Based Systems Engineering using SysML tools (Cameo) and Configuration Management (eB), and is engaging the SKA community activities by the use of on-the-cloud systems for reporting (JIRA) and discussion (Confluence). In this contribution we report how these tools are being used, what is the impact they are having in the SKA design process, their limitations, and the solutions to work around them.

9911-69, Session PSMon

Management aspects of Gemini's base facility operations project

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Gemini's Base Facilities Operations (BFO) Project provided the capabilities to perform routine nighttime operations without anyone on the summit. The expected benefits it were to achieve money savings and to become an enabler of the future development of remote operations.

Managing this project represented several challenges:

It was a schedule driven project.

With limited resources we managed a large number of concurrent work packages.

We had to implement new capabilities without disrupting operations.

And we needed to succeed introducing the new operational model, where operators would rely on technology to assess summit conditions.

The project was executed using a tailored version of Prince 2 project management methodology. We spent a good portion of time early in the project, collecting or learning about user's needs. This was done through close interaction with Telescope Operators and Observers.

Once we had a clear understanding of the requirements and since the project was schedule driven, we took the approach of implementing the "bare minimum" necessary technology that would meet the requirements and that would be maintainable in the long term.

BFO was divided in several smaller projects called work packages (WP). We executed them independently, introduction another important concept called "gradual descent". With this idea in mind, we increasingly provided tools to the night staff to prevent them from going outside the control room during nighttime operations. Also, by using them at an early stage, we had plenty opportunity for debugging and problem fixing.

The main technical areas that BFO tackled were:

• The preservation of safe daytime and nighttime operations. We implemented 3 observatory modes called "Summit, Standby and Base". During the day the observatory remains in Summit mode making the remote operations of the critical systems from the base, impossible. At night the observatory is in Base mode enabling full remote control of the above-mentioned systems and during the period of time that nobody is operating, the observatory is left in Standby mode.

• The creation of a virtual summit operator through the Facility Protection System (FPS) that takes autonomous actions under 3 well identified scenarios: precipitation, earthquake and network loss. In each case the actions and their immediacy is different. For instance, precipitation triggers an immediate dome closing sequence; earthquakes on the other hand are notified if they are small, but systems are stopped if the earthquake is large and in the case of summit-base network loss, FPS waits for few minutes before initiating a closing sequence.

• The replacement of operator's eyes and ears was achieved by adding Video/Audio and Cloud Sensing systems that provide full remote inspection capabilities and nighttime fog and cloud presence assessment. We also implemented redundant weather sensors to monitor conditions that were critical for the safety of the observatory as a whole.

To assure proper BFO overall performance, all WPs products were tested at a system level before releasing them to operations.

Work packages were documented and in each case a formal handover protocol was followed.

We finally conducted 3.5 months of trial operations before declaring the project done.

9911-70, Session PSMon

Diffraction modeling of finite subband EFC probing on dark hole contrast with WFIRST-AFTA shaped pupil coronagraph

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Both shaped pupil coronagraph (SPC) and hybrid Loyt coronagraph (HLC) are of the primary architecture in current coronagraph instrument (CGI) design that is under intense development for a proposed NASA WFIRST-AFTA mission. The SPC operates in two modes: discovery/disk science mode which has a disk shape dark hole region but relatively larger inner working angle (IWA), and characterization mode for Integral filed spectroscopy (IFS) which has sets of bow-tie shaped dark hole regions but smaller IWA. While the current design bandpass of science filter for non-IFS imager has a 10% bandwidth at each band, it generally requires multiple narrow bandpass (subband) filters for accurate E field estimation through a pairwise image plane probing to achieve designed dark hole contrast, in a high contrast coronagraph that uses Electric Field Conjugation (EFC) algorithm for wavefront sensing and control. On the other hand to contain system complexity and cost, it is desirable to have as smaller number of mechanisms as possible. Current CGI design allocates two subband filters per full band. In this paper we investigate, through diffraction modeling with realistic AFTA optics and finite bandwidth EFC probing, the adequacy of such limited number of subband filters in achieving the designed contrast for SPC imager configuration. Multiple subband choices and probing strategies are explored, including standard subband probing; mixed wavelength and/or weighted Jacobian matrix; subband probing with intensity subtraction; and extended subband probing with intensity subtraction. Overall, the investigation shows that the achievable contrast with limited number of finite subband EFC probing is about 2-2.5x worse than the designed post-EFC contrast for current SPC design. Detailed results are included and discussed.

9911-71, Session PSMon

Radiometric model for the stereo-camera STC onboard the BepiColombo ESA mission

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BepiColombo is the fifth cornerstone mission of the European Space Agency (ESA) foreseen to be launched in 2017 with the aim of studying in great detail the Mercury planet.

One of the BepiColombo instruments is the STereoscopic imaging Channel (STC), which is part of the Spectrometers and Imagers for MPO BepiColombo Integrated Observatory SYStem (SIMBIOSYS) suite: an integrated system for imaging and spectroscopic investigation of the Mercury surface.

The main scientific STC objective is the 3D global mapping of the entire surface of Mercury with a scale factor of 60 m per pixel at periherm.

To determine the design requirements and to model the on-ground and in-flight performance of STC, a radiometric model has been developed.

STC optical design, mirrors and lenses specifications together with focal plane assembly (FPA) characteristics have been used as input data to the model for defining the spectral instrument response function. Depending on the applications (i.e. simulation of the instrument behavior in-flight or on-ground during the calibration) different sources can be taken into account as input for the model. Mercury expected radiance, as derived from current available data, or the measured OGSE integrating sphere radiance, or calibrated stellar fluxes can be considered.

Primary outputs of the model are: the expected integration times used on-ground during the calibration campaign and the in-flight exposure time to be used both for surface imaging along the orbit around Mercury and during stellar calibration acquisitions. In addition the expected signal-to-noise ratio (SNR) has been evaluated.

This paper describes the radiometric model structure philosophy, the input and output parameters and presents the radiometric model derived for STC. The predictions of the model will be compared with some measurements obtained during the Flight Model (FM) ground calibration campaign. In particular, the results show that the foreseen values are in good agreement with the measurements.

Finally, the radiometric model can be further improved using the experimental results of the on-ground calibration to better simulate the in-flight performance prediction.

9911-72, Session PSMon

Cooling a solar telescope enclosure: plate coil thermal analysis

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The climate of Haleakal? requires the observatories to actively adapt to changing conditions in order to produce the best possible images. Observatories need to be maintained at a temperature closely matching ambient or the images become blurred and unusable. The Daniel K. Inouye Solar Telescope (DKIST) is a unique telescope as it will be active during the day as opposed to the other night-time stellar observatories. This means that it will not only need to constantly match the ever-changing temperature during the day, but also during the night so as not to sub-cool and potentially affect the view field of nearby telescopes while they are in use. Being located approximately twenty-five (25) meters from operational telescopes, this becomes an issue that should be managed. Currently, there are many systems designed to manage the thermal environment of the observatory. However, the scope of this research was on the carousel cooling system of the DKIST.

The telescope enclosure surface, as mentioned, will be kept near ambient temperature. To accomplish this task, plate heat exchanger panels will be installed on the DKIST enclosure that are designed to keep the temperature at ambient temperature +0°C/-4°C. To verify the feasibility of this and to validate the design models, a test rig has been installed at the summit of Haleakal?. The project's purpose is to confirm that the plate coil panels are capable of maintaining this temperature throughout all seasons and involved collecting data sets of various variables including pressures, temperatures, flows of coolant, solar radiations and wind velocities during typical operating hours. Using MATLAB, a script was written to observe the plate coil's thermal performance. The system did not perform as expected, achieving a surface temperature that was generally 2ºC above ambient temperature. This isn't to say that the plate coil does not work, but the small chiller used for the experiment was undersized resulting in coolant pumped through the plate coil that was not supplied at a low enough temperature. Calculated heat depositions were about 23% lower than that used as the basis of the design for the chillers to be used for the full system, a reasonable agreement given the fact that many simplifying assumptions done in the model. These were not carried over into the testing.

The test rig performance showing a 23% margin provides a high degree of confidence for the performance of the full system when it is installed. If time allows, additional testing could be done that includes additional incident angles and times of day. This would allow a more complete analysis. If additional testing is performed, it's also recommended to use a larger chiller for the plate coil or to set the coolant flowing through the plate coil to a lower temperature. The test rig design could also be optimized in order to bring the plate coil up to its maximum efficiency. In the future, the script could be rewritten in a different computer language, so that the data could be solved for quicker. Further analysis could also include different types of coolants.

9911-73, Session PSMon

The Atacama Large Millimeter/sub-millimeter Array (ALMA) band-1 receiver

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The Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) is currently responsible to contribute the Band 1 (35-50 GHz) receiver system to the ALMA project. Together with the Herzberg Institute of Astrophysics in Canada (HIA), the National Radio Astronomy Observatory (NRAO) in the USA, the University of Chile (UCh) in Chile, and the National Astronomical Observatory of Japan (NAOJ). ALMA Band 1 will be able to study a very broad range of astrophysical environments, from nearby stars

to the re-ionization edge of the Universe. The two main scientific cases of ALMA Band 1 are also two of the ALMA Level One Science Goals: 1) the study of grains in protoplanetary disks to sizes as large as ~1 cm; and 2) the detection of the CO (3--2) line from nearby to high-redshift galaxies (6 < z <10). But, the scientific case for ALMA Band 1 is much more extended: studies of the cold molecular ISM, through the observation of many molecular lines close to their fundamental rotational transitions, which will allow the study of star formation processes in nearby galaxies; the study of the Sunyaev-Zel'dovich effect to probe the physics of galaxy clusters; the study of protoplanetary disks; detection of spinning dust; study of chemical differentiation in cloud cores; solar observation of flares in the Sun; or study of magnetic fields through the use of the Zeeman effect. Band 1 will allow ALMA to bridge the gap between the mm/sub-mm and cm radio astronomy and, given the large ratio of the available bandwidth to frequency, it will be able to study a large range of energy regimes.

The plan is to complete and deliver all 73 receiver units by the end of 2019. Not only are the technical requirements for the receivers far more stringent than any existing receiver system at this frequency band, but also the development and delivery schedule is challenging. To meet this requirement, the integration/test infrastructure and human resources must be planned to sustain the requirements over the next several years. Industrial involvement is also one of the important elements in the project planning. This document will present an overview of the Band 1 receiver project, the status of receiver development, and the progress of establishing the infrastructure and the projected project time-line.

9911-74, Session PSMon

Simulation analysis of the photographic noncoincidence between fiber ends and light spots under integrating sphere light source

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Fiber spectroscopic telescopes, such as LAMOST, require accurate alignment between the fiber ends and their corresponding celestial targets, and thus accurate position measurement of the fiber ends becomes a key problem. Due to the huge amounts and extremely small diameter of the fibers, photogrammetry is the most appropriate technology to measure the positions of all the fiber ends at the same time. In the measurement, the center of a light spot obtained through gray centroid method is regarded as the center of a fiber end. Nevertheless, we've observed that these two centers don't coincide under wide visual angles when integrating sphere is used as light source.To be more specific, there are two phenomena: 1) Under the image coordinate, the center of a light spot is always roughly on the extension line of the image center and the center of an optical fiber end; 2) The shape of captured light spotsturns into approximate ellipse while the visual angle increases. Basing on these phenomena we observed, this paper proposes a hypothesis that the maximum intensity of the light transmitted by the optical fiber to the end of the optical fiber is not in the end of the fiber, but outside the end of the fiber. The intensity distribution at the output end of fibers under integrating sphere light source is simulated by using ZEMAX. ZEMAX is a new type of optical ray tracing program, which can simulate the optical system of light transmission. So the photographic noncoincidence between fiber ends and light spots under integrating sphere light source is simulated and analyzed on ZEMAX.

9911-75, Session PSMon

Point spread function computation in normal incidence for rough optical surfaces

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The Point Spread Function (PSF) allows specifying the angular resolution of optical systems, a key parameter used to define the performances of most of the optics. A prediction of the system's PSF is therefore a powerful tool to assess the design and manufacture requirements of complex optical systems. Usually well-established ray-tracing routines based on a geometrical optics are used for that purpose. However, those ray-tracing routines either lack of real surface defects (figure errors or microroughness) considerations in their computation, or they include a scattering effect modeled separately that requires assumptions difficult to verify. Facing an increasing demand for tighter angular resolution, the problem of surface finishing could drastically damage the optical performances of the system and must be taken seriously, including in optical telescopes systems.

In that context, a purely physical optics approach is more appropriate as it remains valid regardless of the shape and size of the defects appearing on the optical surface. However, such a computation, when performed in the two-dimensional space, is memory and time consuming as it requires one to process a surface map with a few micron resolution, sometimes extending the propagation to multiple-reflections. Fortunately, the computation is significantly simplified in the far-field configuration as it involves only a sequence of Fourier Transforms. In this paper, we show how to account for measured surface defects and roughness in order to predict the performances of the optics in single reflection.

9911-76, Session PSMon

4MOST systems engineering: from conceptual design to preliminary design review

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The 4MOST Facility is a very high-multiplex, wide-field, fibre-fed spectrograph system for the ESO VISTA telescope. Its aim is to create a world-class spectroscopic survey facility that is unique in its combination of wide-field multiplex, spectral resolution, spectral coverage, and sensitivity.

In such a complex instrumentation project, in which design and development activities are geographically distributed through several international institutions, a formal system engineering approach is essential for the success of the project.

After a successful concept optimization design phase, 4MOST entered at the end of 2014 into its Preliminary Design Phase. During this phase, 4MOST Systems Engineering have been challenged to accommodate evolving technical requirements, incomplete definitions of the interfaces with the VISTA Telescope, and undefined operational procedures in a tight schedule. Here we will present the process and tools adopted during the Preliminary Design Phase to perform the requirements analysis and define the subsystems specifications, coordinate the interface control documents and draft the system verification procedures. We will also present the plan

for the main systems engineering activities planned for the Final Design Phase.

9911-77, Session PSMon

Preliminary design of the HARMONI science software

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HARMONI is one of the two first-light instruments that will be installed on the European Extremely Large Telescope (E-ELT) in 2024. It is a visible and near-infrared integral field spectrograph, operating in the wavelength range 0.47–2.45µm. Coupled with two different adaptive optics (AO) systems, it will offer a set of spatial scales and resolutions to optimize observations for a wide range of science programs and observing conditions.

In this paper we present the science software that is being developed for the HARMONI instrument.

The Instrument Numerical Model (INM) simulates the instrument from the optical point of view, in order to provide synthetic exposures simulating detector readouts, and includes the whole chain of acquisition from the atmosphere down to the telescope and including the detectors. It is based on Fourier optics formalism taking into account both optical aberrations and diffraction effects, by propagating a wavefront through the instrument. The adaptive optics simulation is provided by a dedicated model delivering PSFs.

The Data Reduction Software (DRS) removes most of the instrumental signature from raw data frames, corrects the data from the environmental effects (e.g. atmospheric refraction, sky background) and converts them into a fully calibrated, scientifically usable data cube. To improve the data quality it will use only a single re-sampling step from the raw data to the reduced data-cube.

These two software packages benefit from being developed together in a closed loop. The INM transforms data-cubes containing astrophysical scenes or test data into simulated detector exposures, and the DRS turns them back into a data-cube. By comparing a specially created data-cube at the INM entrance with the output at the DRS level it becomes possible to validate the simulation and the reduction of each effect individually. However these two software packages will be developed in different contexts. The INM is a living software evolving as the instrument is being designed and built, and thus must be flexible enough to easily simulate new effects. The DRS has to be developed within an ESO framework, and will be available to every observer who needs to reduce data taken with HARMONI.

This paper presents the functionalities and the preliminary design of this software, describes some of the methods and algorithms used and highlights the challenges that we will have to face.

9911-78, Session PSMon

CARMENES: system engineering during manufacturing and AIV phases

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CARMENES (Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs) is a high resolution spectrograph built for the 3.5m telescope at the Calar Alto Observatory (Almería, Spain), which is operated jointly by the Max-Planck-Society (MPG) and the Spanish National Research Council (CSIC). CARMENES consists of two separated highly stabilized spectrographs covering both the visible, from 0.5 to 1.0 µm, and the near-IR, from 1.0 to 1.7 µm, wavelength ranges and long term stability with spectral resolution of R=82,000 to provide high-accuracy radial-velocity measurements (?1 m/s) and long-term stability.

CARMENES has been built by a consortium formed by five German institutions, five Spanish institutions and the Calar Alto observatory itself. The instrument first light took place on November, 9th 2015 to start operations on January 1st 2016.

The technical and managerial complexity of the instrument demanded a strong system engineering control during the system development, manufacturing, assembly, integration and verification. The goal was to ensure that the demanding high level requirements were met. The MPG and CSIC, the observatory's owners, imposed CARMENES to be ready for operations at the end of 2015, which was an important constrain that impacted on all technical decision taken during the last project phases.

The system engineering activities carried out during those project phases included a) preparing the specifications of low-level subsystems and components, and implementing traceability of the high-level requirements to the low-level ones, b) follow up of components manufacturing to verify that low-level specifications were fulfilled, c) definition and control of the interfaces between subsystems and components developed by the different teams and external providers, d) coordination of the preparation of the observatory rooms to be ready for receiving the instrument, e) preparation and control of the AIV plans followed at the different centers before acceptance and delivery of the main subsystems to the observatory and f) coordination of the AIV phase at system level at the observatory.

This article summarizes how these activities were carried out in order to have CARMENES fully operational on the imperative date.

9911-79, Session PSMon

ALMA software release management: a practical approach

Rubén Soto, Tzu-Chiang Shen, ALMA (Chile); Jorge Ibsen, European Southern Observatory (Germany); Norman Saez, ALMA (Chile); Erich Schmid, A. Maurizio Chavan, European Southern Observatory (Germany)

The ALMA software is a large collection of modules implementing all the functionality needed for the observatory's day-to-day operations from proposal preparation to the scientific data delivery. ALMA software subsystems include among many others: array/antenna control, correlator, telescope calibration, submission and processing of science proposals and data archiving.

The implementation of new features and improvements for each software subsystem must be in close coordination with observatory milestones, the need of rapidly respond to operational issues, regular maintenance activities and testing resources available to verify and validate new and

improved software capabilities. This paper described the main issues detected managing all these factors together and the different approaches used by the observatory in the search of an optimal solution.

We describe the software delivery process adopted by ALMA since the construction phase and its further evolution in early operations. We also present the acceptance mechanism implemented by the observatory for the validation of the software before it can be used for science operations. We provide details of the main roles and responsibilities in the software delivery and validation and their participation at the process for reviewing and approving changes into the accepted software versions.

Finally, we present ideas on how these processes should evolve in the near future, considering the operational reality of the ALMA observatory as it moves into full operations. We summarize the progress implementing some of these ideas and lessons learnt.

9911-80, Session PSMon

NELIOTA: ESA's new NEO lunar impact monitoring project with the 1.2m telescope at the National Observatory of Athens

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NELIOTA is a new ESA activity launched at the National Observatory of Athens in February 2015 aiming to determine the distribution and frequency of small near-earth objects (NEOs) via lunar monitoring. The project involves: (i) a complete refurbishment of the 40 year old 1.2m Kryoneri telescope at the National Observatory of Athens, (ii) development of a Lunar imager for the prime focus with two fast-frame sCMOS cameras, and (iii) procurement of servers for data processing and storage. Furthermore, we have developed a software system that controls the telescope and the cameras, processes the images and automatically detects lunar flashes. NELIOTA provides a web-based user interface, where the impact events, after their verification and characterization, will be reported and made available to the scientific community and the general public. The objective of this 3.5 year activity is to design, develop and implement a highly automated lunar monitoring system, which will conduct an observing campaign for 2 years, starting in the Summer 2016, in search of NEO impact flashes on the Moon. The novelty of this project is the dedication of a large, 1.2m telescope for lunar monitoring, which is expected to characterize the frequency and distribution of NEOs weighing as little as a few grams.

9911-81, Session PSMon

Design and test of a tip-tilt controller for an image stabilization system

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This work consists on the description of the whole development process of a tip-tilt controller. This controller will be part of an Image Stabilization System of the PHI instrument of the Solar Orbiter mission. The main characteristics of this controller are high output voltage levels and a high resolution. The development process includes the design, tests and verification steps.

Simulations have been carried out for supporting the design step and allowing for the consecution of the specified requirements for the mission. Simulation results will be compared to the measurements obtained for the engineering model.

A thorough test of the controller has been performed. The controller output achieves a minimum output resolution of ±14mV and a maximum current consumption of 13mA rms.

9911-82, Session PSMon

SIMCADO: how to use the end-to-end model of the E-ELT's first-light near-infrared wide-field imager

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The era of the ELTs will soon be upon us and with it the ability to observe smaller, fainter and more distant objects than ever before. MICADO will be the E-ELT's first-light near-infrared wide-field camera, providing diffraction limited imaging over a ~50 arcsec field of view. During the development of such an instrument it is imperative that all parties (i.e. the design, calibration, and science teams) have a platform with which to exchange information regarding the current state of instrument. In this context we are developing an end-to-end instrument data simulator for MICADO - SimCADO.

SimCADO is able to simulate the entire optical path between a source and the MICADO focal plane array. To do this we have used a modular array-based approach (instead of a ray tracing approach), implemented in python in order to minimize computation time and maximize the potential user base. The array based approach means that SimCADO can be run on everyday computers in a "usable" time frame (seconds to minutes). The intrinsic modularity means that we are able to update SimCADO with the newest optical design as soon as the data becomes available. Naturally we provide data for the current design of the E-ELT/MICADO optical train, however the user may use her or his own instrumental data and still retains complete control over the whole system.

Here we present an overview of how to use the SimCADO package, both for the quick-use case where the user would like to visualise an object of interest as seen by MICADO, as well as for the advanced case, where the user would like to simulate MICADO output images under varying conditions and instrument configurations.

9911-83, Session PSMon

Simulating the LSST OCS for conducting survey simulations using the LSST scheduler

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During the past 10+ years of project definition, the Operations Simulator was used to prototype the LSST Scheduler. Moving towards operations, the Scheduler is being developed as a separate project to interface with the LSST Observatory Control System (OCS). A new Simulator is under concurrent development to adjust to this change of architecture. It consists of the Scheduler and a package that will simulate enough of the OCS interfaces to allow execution of realistic schedules. This new package is called the Simulated OCS (SOCS).

The SOCS is responsible for collecting control (time, downtime, mode, etc.), configuration (observatory, proposals, etc.) information and environmental conditions (seeing, clouds, etc.) and transmitting the data to the Scheduler. The Scheduler performs the operations necessary to produce the next target or targets for observation. The SOCS then carries out the observation and returns that observation (visit) back to the Scheduler. The SOCS will also record target, observation, Scheduler telemetry, observatory state and other information into a simulated survey database.

This paper will detail the construction plan for SOCS and provide information about its package structure and use of the LSST communication middleware platform that is built on top of the Data Distribution Service (DDS) standard. It will also describe some interesting use cases that the separated architecture allows. The software engineering practices used during the code development process will also be elaborated.

9911-84, Session PSMon

Quality initiative at ESO

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An initiative is under way at ESO Headquarters to streamline operations, in particular in the engineering, technical and associated management areas. A systematic approach to strengthen the operating processes is in preparation, starting with a mapping of the extensive existing process network. Processes identified as sufficiently important and complex to merit an in-depth analysis will be properly specified and their implementation optimised to strike a sensible balance between organisational overhead (documentation) and efficiency. By applying methods and tools tried and tested in industry we expect to achieve a more unified approach to address recurrent tasks. This will enable staff to concentrate more on new challenges and improvement rather than spending effort on issues already resolved in the past.

9911-85, Session PSMon

SHARK-NIR system design analysis overview

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In this paper, we present an overview of the System Design Analysis carried on for SHARK-NIR, the coronagraphic camera designed to take advantage of the outstanding performance that can be obtained with the FLAO facility at the LBT, in the near infrared regime. Born as a fast-track project, the system now foresees both coronagraphic direct imaging and spectroscopic observing mode, together with some wavefront correction tools. The analysis we report here includes several trade-offs for the selection of the baseline design, in terms of optical and mechanical engineering, and the choice of the coronagraphic techniques to be implemented, to satisfy both the main scientific drivers and the technical requirements set at the level of the telescope. Further care has been taken on the possible exploitation of the synergy with other LBT instrumentation, like LBTI. A set of system specifications is then flown down from the upper level requirements to finally ensure the fulfillment of the science drivers. The preliminary performance budgets are presented, both in terms of the main optical planes stability and of the image quality, including the contributions of the main error sources in different observing modes.

9911-86, Session PSMon

Integrated opto-dynamic modeling of the 4m DAG telescope image quality performance

Lorenzo Zago, Benjamin Guex, HEIG-VD (Switzerland)

The Turkish DAG 4-m telescope is currently through the final design stage with major optics parts already ordered.

It is to be located on a 3000 m mountain top in Easter Anatolia.

The telescope will be a state-of-the art device, alt-az mount with active primary and adjustable secondary and tertiary mirrors. Its optics design is specially aimed at being compatible with advance adaptive optics instrumentation.

The ultimate performance of such a telescope results of multiple concurrent effects from many different components and active functions of the complex system.

The paper presents a comprehensive integrated (end-to-end) model of the telescope, comprising in one computational sequence all structural, electrodynamics and oactive optics performance that produce the image quality at the focal plane.

The model is entirely programmed in Matlab/Simulink and comprises a finite element model or structure and mirrors, dynamics modal reduction, deformation analyses of structural and optical elements, active optics feedback control in the Zernike modal space.

9911-87, Session PSMon

SysML model of exoplanet archive functionality and activities

Solange Ramírez, California Institute of Technology (United States)

The NASA Exoplanet Archive is an online service aimed to promote and enable astronomical research related to search for and characterization of extrasolar planetary systems. We are dedicated to collect and serve

important public data sets and provide tools to work with these data. Data include stellar parameters, exoplanet parameters, time series, images, and spectra. Tools provided are interactive tables, plotting and histogram tool, time series viewer, transit predictor, periodogram service, and application program interfaces. There are many interfaces and interactions between data in our database and file systems and the tools we provide to the users. Our weekly additions of data and updated to the services are complex and need to be managed efficiently. The SysML model presented here help us through the weekly update process. The model includes Package Diagrams to show the overall structure of the model, block definition diagrams to present the logical architecture, and behavioral diagrams (activity and sequence) to describe the weekly update process.

9911-88, Session PSMon

Optomechanical design software for segmented mirrors

Juan Marrero, European Southern Observatory (Germany)

The design of an optomechanical system, especially of large telescopes, involves the consideration of thousands of highly interrelated parameters. Many commercial tools like Matlab, Ansys, Zeemax or Inventor, covering various disciplines like Mathematical analysis, Finite Element Modelling, Optical Design or CAD modelling, need to be employed in a certain order to obtain final conclusions on the performances of the system.

The description of a software tool under development is presented in this article. This tool pretends to ease the parametric analysis of large structures, allowing on the fly results at the change of a paremeter, without the need for going from one software package to another.

A brief summary of the most important features implemented on the described application follows:

- Solid and segmented mirrors analysis
- Ray tracing
- AIV errors analysis
- Collision detection
- 3d graphical representation
- Adaptable on-the-fly structure creation
- Supports analysis
- Deflections computation (through Ansys)
- Analysis of segmented mirror related components: Edge Sensors misalignments, Position Actuators stroke optimization, Warping Harness wavefront maps, etc.
- Export CAD models
- Accessibility analysis

At present, the tool is being very useful on the analysis of the various E-ELT error budgets, together with many other aspects.

9911-89, Session PSMon

Making the most of MBSE: pragmatic model-based engineering for the SKA Telescope Manager

Gerhard Le Roux, SKA South Africa (South Africa); Alan Bridger, Michael J. MacIntosh, Mark Nicol, Hermine Schnetler, Stewart J. Williams, UK Astronomy Technology Ctr. (United Kingdom)

Many large projects including major astronomy project are adopting a Model Based Systems Engineering approach. How far is it possible to get value for the effort involved in developing a model that accurately represents a significant project such as SKA? Is it possible for such a large project to ensure that high-level requirements are traceable through the various system-engineering artefacts? Is it possible to utilize the tools available to produce meaningful measures for the impact of change?

This paper shares one aspect of the experience gained on the SKA project. It explores some of the recommended and pragmatic approaches developed, to get the maximum value from the modelling activity while designing the Telescope Manager for the SKA. While it is too early to provide specific measures of success, certain areas are proving to be the most helpful and offering significant potential over the lifetime of the project.

The experience described here has been on the Cameo Systems Modeller tool set, supporting a SysML based System Engineering approach; however the concepts and ideas covered would potentially be of value to any large project considering a Model based approach to their Systems Engineering.

9911-90, Session PSMon

Tolerancing a radial velocity spectrometer within Zemax

Steven R. Gibson, Univ. of California, Berkeley (United States); Steven R. Gibson, Space Sciences Lab. (United States)

Techniques are described for tolerancing a radial velocity spectrometer system within Zemax, including: how to set up and verify the tolerancing model, performance metrics and tolerance operands used, as well as post-Zemax analysis methods. Use the tolerancing model for various analyses will be discussed, such as: alignment sensitivity, radial velocity sensitivity, and sensitivity of the optical system to temperature changes. Tolerance results from the SHREK project (a precision radial velocity spectrometer of asymmetric white pupil design) will be shown.

9911-91, Session PSMon

A method for generating a synthetic spectrum within Zemax

Steven R. Gibson, Edward Wishnow, Space Sciences Lab. (United States); the SHREK collaboration ., UC Berkeley Space Sciences Laboratory (United States)

A method using non-sequential Zemax to produce a pixelated synthetic spectrum is described. This simulation was developed for the SHREK project (a precision radial velocity spectrometer of asymmetric white pupil design). The synthetic spectrum will prove useful for engineering performance analyses (instrument stability, stray light, cross-talk between orders, camera distortion, line shape profile, etc.). It has also provided a base set of synthetic spectra to be used during the development of the data pipeline. Various aspects concerning the construction of the spectrum are described, including: converting a model from sequential to non-sequential Zemax, the creation of Zemax coating files for echelle blaze functions and overall system efficiency, and the generation of spectrum source files (solar, thorium-argon, incandescent, Fabry-Perot etalon and laser frequency comb).

9911-92, Session PSMon

LSST telescope modeling overview

Jacques Sebag, LSST (United States); Michael Warner, LSST (Chile); William J. Gressler, Constanza Araujo Hauck, John Andrew, Ming Liang, Douglas Neill, Felipe Daruich, Sandrine J. Thomas, Myung Kyu Cho, George Z. Angeli, LSST (United States)

During this early stage of construction of the LSST telescope, modeling has become a crucial system engineering process to ensure that the final detailed design of all the sub-systems that composed the telescope meet requirements and interfaces. This activity is particularly important because of the increased complexity of the telescope systems. Modeling includes multiple tools and type of analyses that are performed to address specific technical issues. 3D Computer-aided Design (CAD) modeling has become central for controlling interfaces between subsystems and identifying potential interferences. In addition, maintenance and handling requirements can be verified using 3D models.

The LSST Telescope dynamic requirements are challenging because of the nature of the LSST survey which requires a high cadence of rapid slews and short settling times. Combination of finite element modeling (FEM) coupled with control system dynamic analysis has proven to provide a method to validate these specifications. The output of the structural FEM analysis is key to provide the matrices for the nodal or modal model of the subsystem response. The dynamic analyses are implemented in Matlab using the object-oriented Simulink environment.

These challenging slewing requirements have a direct impact on the LSST primary/tertiary mirror support system that must be able to prevent excessive loads on the six locating actuators to maintain the mirror in place in real time. Modeling the behavior of the pneumatic actuators that support the mirror is required to develop the control strategy to counteract for these dynamic forces during slewing.

An overview of these modeling activities will be given in this paper including specific cases relevant to LSST.

9911-93, Session PSMon

Daniel K. Inouye Solar Telescope systems engineering update

Robert P. Hubbard, Simon C. Craig, Ruth A. Kneale, National Solar Observatory (United States)

The Daniel K. Inouye Solar Telescope (DKIST), formerly the Advanced Technology Solar Telescope (ATST), is now in its sixth year of construction. During the two years that have elapsed since our last systems engineering update we have been through factory acceptance of several major subsystems including the enclosure, telescope mount assembly, and the primary mirror. With these major milestones behind us, site assembly in progress, and with the integration, test, and commissioning phase about to begin, we will discuss what has been working well in terms of DKIST systems engineering processes along some things we could have done better and would do differently if given another chance. The paper examines examples of successes including full-scale factory assembly of major mechanical components and some less optimum outcomes. We explore the reasons for success or failure, including the early delivery and level of detail in factory acceptance test procedures.

9911-94, Session PSMon

End-to-end modeling: a new modular and flexible approach

Matteo Genoni, INAF - Osservatorio Astronomico di Brera (Italy) and Univ. degli Studi dell'Insubria (Italy); Marco Riva, Marco Landoni, Giorgio Pariani, INAF - Osservatorio Astronomico di Brera (Italy)

In this paper we present an innovative philosophy through which develop the End-to-End model for astronomical observation projects, i.e. the architecture which allows physical modeling of the whole system from the light source to the reduced data. This new philosophy foresees the development of the physical model of the different modules, which compose the entire End-to-End system, directly during the project design phase. This approach is strongly characterized by modularity and flexibility; these aspects will be extremely required in the next generation astronomical observation projects like E-ELT (European Extremely Large Telescope) because of the high complexity and long-time design and development. With this approach it will be possible to keep the whole system and its different modules efficiently under control during every project phase and to exploit a reliable tool at a system engineering level to evaluate the effects on the final performance both of the main parameters and of different instrument architectures and technologies. This philosophy will be important to allow scientific community to do in advance simulations and tests on the scientific drivers. This will translate in a continuous feedback to the (system) design process with a resulting improvement in the effectively achievable scientific goals and consistent tool for efficiently planning observation proposals and programs. We present the application case for this End-to-End modeling technique, which is the high resolution spectrograph at the E-ELT (E-ELT HIRES). In particular we present the definition of the system modular architecture, describing the interface parameters and detailed model of the modules.

9911-95, Session PSMon

Concept of operations (a day in the life) of the COSMO large coronagraph

Phillip H. Oakley, Steven Tomczyk, Scott Sewell, Dennis J. Gallagher, Brandon Larson, Alice R. Lecinski, Greg L. Card, Rob Graves, National Ctr. for Atmospheric Research (United States)

The COronal Solar Magnetism Observatory (COSMO) Large Coronagraph is a proposed facility with unique capabilities for magnetic field measurements in the solar corona. This paper summarizes the preliminary concept of operations of this facility. Specifically we detail a "day in the life" of the observatory discussing both the synoptic program and guest program. We also detail the daily schedule of the observer, facility, and scientific instrument. Lastly community interaction with the facility is discussed from the perspective of observation planning, proposing, observing, data pipeline processing, and data delivery.

9911-96, Session PSMon

Systems engineering overview of the COSMO large coronagraph

Phillip H. Oakley, Steven Tomczyk, Scott Sewell, Dennis J. Gallagher, Brandon Larson, Alice R. Lecinski, Gregory L. Card, Rob Graves, National Ctr. for Atmospheric Research (United States)

The COronal Solar Magnetism Observatory (COSMO) Large Coronagraph is a proposed facility with unique capabilities for magnetic field measurements in the solar corona. This paper summarizes the systems engineering plan for this facility. In particular we detail the flow of science requirements to engineering requirements, and discuss an overview of requirements management, configuration management and overall verification and compliance processes.

9911-97, Session PSMon

An optical toolbox for astronomical instrumentation

Brian M. Sutin, Thirty Meter Telescope (United States)

The author has open-sourced a program for optical modeling of astronomical instrumentation. The code allows for optical systems to be described in a programming language. An optical prescription may contain coordinate systems and transformations, arbitrary polynomial aspheric surfaces and complex volumes. Rather than using a plethora of rays to evaluate performance, all the derivatives along a ray are computed by automatic differentiation. By adaptively controlling the patches around each ray, the system can be modeled to a guaranteed known precision. The code currently consists of less than 10,000 lines of C++/stdlib code.

9911-98, Session PSMon

Reduced order transfer function for a radio-telescope

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A frequency response analysis for the identification of the dynamical model for a 34 meters radiotelescope was performed. The model identified is a 18th-order linear transfer function, which has its main resonances into the range from 1 to 10 Hz.

In this work just the nearby resonances of the frequency response and their modal shapes were considered to get a reduced order model, by performing a new methodology which its main concern is to reproduce the embodied frequency response.

This methodology consists of a set of steps which were embodied in a Transfer Function Reconstruction algorithm. The application of this function shows systematically how the identification, classification, and treatment of truncation unwanted factors from the frequency response analysis is performed.

The model validation was made by performing responses analysis: time and frequency. Here a second iterative algorithm was used to relocate the poles of the reduced order transfer function to mitigate the magnitude of the oscillations from time step inputs, like a fine tuning of these poles.

A second validation for the reduced order transfer function of the radio telescope model was controlled by simulating the sun tracking from position commands based on NOAA Solar Position Algorithm. The simulation results show that this complete methodology is competitive with others documented before.

9911-99, Session PSMon

Optical parametric evaluation model for a broadband HIRES at E-ELT

Matteo Genoni, INAF - Osservatorio Astronomico di Brera (Italy) and Univ. degli Studi dell'Insubria (Italy); Marco Riva, Manuele Moschetti, Matteo Aliverti, INAF - Osservatorio Astronomico di Brera (Italy)

We present the details of a paraxial parametric model of an high resolution spectrograph which can be used as a tool, characterized by good approximation and reliability, at a system engineering level. This model can be exploited to perform a preliminary evaluation of the di?erent parameters as long as di?erent possible architectures of high resolution spectrograph like the E-ELT HIRES. The detailed equations flow concerning the first order e?ects of all the spectrograph components is described; in addition a comparison with the data of a complete physical ESPRESSO spectrograph model is presented as a model proof.

9911-100, Session PSMon

A green observatory in the Chilean Atacama desert

Michael Ramolla, Christian Westhues, Moritz Hackstein, Ruhr-Univ. Bochum (Germany); Klaus W. Hodapp, Univ. of Hawai'i (United States); Rolf Chini, Martin Haas, Ruhr-Univ. Bochum (Germany); Angie Barr Domínguez, Univ. Católica del Norte (Chile); Roland Lemke, Luftfahrt-Bundesamt (Germany); Miguel G. Murphy, Univ. Católica del Norte (Chile)

Since 2007, the Ruhr-Universität Bochum, Germany and Universidad Catolica del Norte, Chile jointly operate the Observatory Cerro Armazones, which is located in direct neighborhood of the future E-ELT of ESO. It is the only observatory that relies completely on green energy. Our electricity is produced by solar panels and windmills. Excess power is stored in batteries that allow uninterrupted operation even in windless nights.

The scientific equipment consists of three robotic optical telescopes with apertures ranging from 15 cm (RoBoTT) over 25 cm (BEST II) to 40 cm (BMT) and one 80 cm (IRIS) infra-red telescope. The optical telescopes are equipped with Johnson and Sloan broad band filters together with a large number of narrow and intermediate bands. In the infrared, J, H and K filters are available, accompanied by several narrow bands near the K band wavelength. A switch of nasmyth foki in the 80 cm telescope allows to use a high resolution echelle spectrograph similar to the FEROS instrument of ESO. This variety has evolved from different collaborations, i.e. with the University of Hawaii which provided the near-infrared-camera of the IRIS telescope, or with the "Deutsches Zentrum für Luft- und Raumfahrt" (DLR) which provided the whole BEST II telescope. The highly automatized processes on all telescopes enable a single person to run the whole facility, providing the high cost efficiency required for an university observatory.

While the comparatively small apertures are not efficient for observing faint sources, the excellent site conditions allow projects that require continuous daily reobservations of astronomical objects over epochs of several months or even years. Such observations are time allocation-wise impossible on the large multinational observatories. We can show that a small collaboration between universities is able to design and operate a green observatory. This enables us to do competitive science, such as studies of young stellar objects, multiplicity of stars, quasar variability or the hunt for exo-planets.

9911-101, Session PSMon

Vibration measurements of the DKIST mount, Coude rotator, and enclosure assemblies

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The Daniel K. Inouye Telescope (DKIST) will be the largest solar telescope in the world, with a 4-meter off-axis primary mirror and 16 meter rotating coude laboratory within the telescope pier. The off-axis design requires a mount similar in size to an 8-meter on-axis telescope. Both the telescope mount and the coude laboratory utilize a new bearing technology in place of hydrostatic bearings. The telescope enclosure utilizes a crawler

mechanism for the altitude axis. As these mechanisms have not previously been used in a telescope, understanding the vibration characteristics and the potential impact on the telescope image is important.

This paper presents the methodology used to perform jitter measurements of the enclosure and the mount bearings and servo system in high-noise environments utilizing seismic accelerometers and high dynamic-range data acquisition equipment, along with digital signal processing (DSP) techniques. Data acquisition and DSP were implemented in MATLAB.

In the telescope mount tests, multiple accelerometers were strategically located to capture the six axes-of-motion of the primary and secondary mirror dummies. The optical sensitivity analysis was used to map these mirror mount displacements and rotations into units of image motion on the focal plane.

Testing was performed by recording accelerometer data while the telescope control system performed tracking operations typical of various observing scenarios. The analysis of the accelerometer data utilized noise-averaging FFT routines, spectrograms, and periodograms. To achieve adequate dynamic range, the use of special filters and advanced windowing functions were necessary. Multiple automated over-night tests were performed and compared to find and select the data sets with the lowest level of external interference.

Similar testing was performed on the telescope enclosure during the factory test campaign. The vibration of the enclosure altitude and azimuth mechanisms are characterized.

9911-102, Session PSMon

Quality management in Laboratory of Space Studies and instrumentation in astrophysics

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From the design of astronomical instruments to the exploitation of results, scientific themes developed at LESIA cover many areas of astrophysics. The activities are organized around projects (ground, space or modeling) whose many accomplishments demonstrate the laboratory's reputation.

The technical quality culture is transmitted between our engineers and technicians mainly through our space projects.

Product assurance management is a main activity in the development of space projects.

The principal activity of a product assurance manager (PAM) in the design phase is to demonstrate that quality applied to product design is under control.

It also has the role:

- to assist the project manager in the mastery of design (support for procurement activities, mastery of changes, risk management...)

- to work with the engineer system to preserve quality performance and reduce risk

In AIT phase (assembly, integration, test) the principal activity of a PAM is to define a quality program that demonstrates that quality controls are carried out and that the quality structure works.

It also has the role:

- to assist the project manager in the mastery of production (support for configuration changes and traceability of equipment, checking supplies comply with the requirements, available documentation preparation coordination)

- to monitor compliance with the requirements

To strengthen this activity, the CNES (French national space research center) and INSU (Universe Sciences National Institute) support the establishment of a quality framework, established by a head quality manager mandated by the laboratory director to coordinating quality activities in the lab.

The main objectif of the Head quality manager is to consolidate, track and reliable "best practices" on lab projects to ensure the satisfaction and the trust of customers, and in particular national and international agencies

Also he can be a guide by simplifying information searches (normative or other) and keep alive the quality system in inter-project periods

9911-103, Session PSMon

Production of ELZM mirrors: performance coupled with attractive schedule, cost, and risk factors

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Extreme Lightweighted ZERODUR® Mirrors (ELZM) have been developed to exploit the superb thermal characteristics of ZERODUR®. Coupled with up to date mechanical and optical fabrication methods this becomes an attractive technical approach. However the process of making mirror substrates has demonstrated to be unusually rapid and especially cost-effective. ELZM is aimed at the knee of the cost as a function of lightweighting curve. ELZM mirrors are available at 88% lightweighted. Together with their low risk, low cost production methods, this is presented as a strong option for NASA Explorer and Probe class missions.

9911-104, Session PSMon

A database for TMT software interface control documents

Kim Gillies, Scott C. Roberts, John Rogers, Thirty Meter Telescope (United States)

The TMT Software System consists of software components that interact with one another through a software infrastructure called TMT Common Software (CSW). CSW consists of software services and library code that is used by developers to create the subsystems and components that participate in the software system. CSW also defines the types of components that can be constructed and their roles. The use of common component types and shared middleware services allows standardized software interfaces for the components.

A software system called the TMT Interface Database System was constructed to support the documentation of the interfaces for components based on CSW. The programmer describes a subsystem and each of its components using JSON-style text files. A command interface file describes each command a component can receive and any commands a component sends. The event interface files describe status, alarms, and events a component publishes and status and events subscribed to by a component. A web application was created to provide a user interface for the required features. Files are ingested into the software system's database. The user interface allows browsing subsystem interfaces, publishing versions of subsystem interfaces, and constructing and publishing interface control documents that consist of the intersection of two subsystem interfaces. All published subsystem interfaces and interface control documents are versioned for configuration control and follow the standard TMT change control processes. Subsystem interfaces and interface control documents can be visualized in the browser or exported as PDF files.

The web application is implemented in the Scala using the Play web application framework. The JSON model files are stored as binary files in the MongoDB document database system. The user interface is created

using Scala.js. All the implementation products are open-source. The source code for the TMT Interface Database System is available on Github.

9911-105, Session PSMon

Stress and thermal optical effects in large refracting corrector elements for the GMT

Sean Lin, Andrew P. Rakich, GMTO Corp. (United States)

The Giant Magellan Telescope (GMT) will consist of seven 8.4 m aperture telescopes mounted as a phased radially symmetrical array in a common mount. One of the observing modes offered by the telescope has a 20 arc minute diameter field, corrected for seeing limited observation. In this mode a large aberration and atmospheric dispersion corrector (C-ADC), with refracting elements of the order of 1.5 m in diameter, provides correction for both the optical design residual astigmatism and atmospheric dispersion. A refracting corrector of this size is unique, and due to its scale, the large refracting components can produce significant wavefront error via mechanisms that are often not significant in smaller correctors. This paper focusses on two of these potential error sources; varying stress within the material leading to birefringence effects, and inhomogeneous thermal distributions leading to deltas in refractive index through the material.

Little work has been done in the area of stress optical modeling of astronomical refracting correctors. For smaller correctors, using standard optical glasses, these effects are often negligible. Variable stresses can arise in the large refractive components from both their variable orientation with respect to gravity and from differential thermal expansions within the correct element material. We have found that there are non-negligible contributions from stress induced wavefront error in elements of our ADC. These stresses have been modeled for a variety of cases with finite element tools, and the resultant wavefront error analyzed with SigFit™ and Zemax™. Details of this integrated modeling approach and the results are presented here.

In a similar integrated modeling approach, ANSYS™ software has been used to produce a transient thermal analysis, and the resultant temperature distribution of the optical elements at specific time has been fed into the SigFit™ Thermo-Optic module and the resultant OPD map fit with Zernike polynomials.

After presenting the results of this analysis we will discuss how the results have informed and guided the opto-mechanical design process, particularly for lens-to-cell interfaces, and how predicted residuals of wavefront error contribute to the overall wavefront error budget for the corrector.

9911-106, Session PSMon

Observatory building design: a case study of DAG with infrastructure and facilities

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DAG (Eastern Anatolia Observatory in Turkish) site is located at 3170 m altitude in one of the well-known mountain ridges of Erzurum, Turkey. As well as erecting the largest telescope of Turkey, the DAG project aims to establish an observatory complex both small in size and functional enough to give service to all astronomy community. In this paper, the challenge is explained in details: geological limitations, usage distribution of building base area, concept of green-building, astronomical services (both on-site and remote), and of course give chance to out-reach of astronomy.

9911-107, Session PSMon

High-contrast imaging and high dispersion spectroscopy observation of exoplanets and brown dwarfs

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Characterizing exoplanet atmospheres is the logical next step after an overwhelming number of discoveries. Current challenges for exoplanet atmosphere characterization are (1), high contrast between and host star and its planet; (2), degeneracy between models at low spectral resolution. High contrast imaging (HCI) and high dispersion spectroscopy (HDS) observation is a promising technique to meet these two challenges. We study system performance of HCI+HDS instrument by exploring a broad range of instrumental and astrophysical parameter spaces. We discuss the implications of this study in two scientific cases: (1) measuring atmospheric chemical composition, (2), probing surface non-uniformity caused by clouds.

9911-108, Session PSMon

AETC: a powerful web-tool to simulate astronomical images

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We present the capabilities of the Advanced Exposure Time Calculator (AETC), a tool, publicly available via a web interface (http://aetc.oapd.inaf.it/), aimed to simulate astronomical images obtained with any (given) telescope and instrument configuration. The tool includes the possibility of providing an accurate modelling of PSF variations in the FoV, a crucial issue for realistic simulations and which makes AETC particularly suitable for simulations of adaptive optics instruments.

The input configuration includes the characteristics of the telescope, instrument and the detector. For selected targets (stars, galaxies, complex objects) the tool provides estimate of S/N for given observations parameters (exposure time, number of exposures, sky conditions, etc). Pre-configured templates are also available for several sets of telescope/instrument, both existing and future, usable as is or as a starting point for a new configuration. In addition AETC produces simulated images of the observations taking into account the instrument configuration and the observation parameters. The observed fields can include not only stars and galaxies, but also any kind of complex object, modelled by convolution with the instrumental PSF.

The PSF can be modelled by a simple function (Gaussian or Moffat), using a radial average brightness profile or a fits image. We will describe how AETC can manage PSFs variable in the FoV and what kinds of input are required. In particular, the user can choose between two options of input data: one (a map that describes the changes of a reference PSF model in terms of ellipticity, FWHM and position angle) well suited for existing instruments, for which the variability of the PSF can be characterized analyzing real images, and one more useful for instruments in development, a data cube of fits images of PSF computed (e.g. with ray-tracing tools) at various positions of the FoV.

The simulated images can be used to estimate the performance of a novel system, but also fed to the analysis tools to characterize the accuracy of the measurements of the science parameters on the real data. In the context of design and concept study of new telescopes and instrumentation, AETC offers the possibility to evaluate the science capability, performing end-to-end simulations of specific science cases. To exemplify the AETC capabilities we will present a number of simulations for specific science cases, useful for studying the capabilities of next generation AO imaging cameras for Extremely Large Telescopes.

9911-35, Session 8

Evaluation of the alignment plan for the Thirty Meter Telescope using optical modeling

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We present an estimate of the optical performance of the Thirty Meter Telescope (TMT) after execution of the full telescope alignment plan. The TMT alignment is performed by the Global Metrology System (GMS) and the Alignment and Phasing System (APS). The GMS first measures the locations of the telescope optics and instruments as a function of elevation angle. These initial measurements will be used to adjust the optics positions and build initial elevation look-up tables.

After this step, the telescope is aligned using starlight as the input for the APS at multiple elevation angles. APS measurement is used to refine the telescope alignment to build elevation and temperature dependent look-up tables. Due to the number of degrees of freedom in the telescope (over 10,000), the ability of the primary mirror to correct aberrations on other optics, the tight optical performance requirements and the multiple instrument locations, it is challenging to develop, test and validate these alignment procedures. In this paper, we consider several GMS and APS operational scenarios. We apply the alignment procedures to the model-generated TMT, which consists of various quasi-static errors such as polishing errors, passive supports errors, thermal and gravity deformations. Using an integrated optical model and Monte-Carlo framework, we evaluate TMT's aligned states using optical performance metrics at multiple instrument and field of view locations. The optical performance metrics include the Normalized Point Source Sensitivity (PSSN), RMS wavefront error before and after Adaptive Optics (AO) correction, pupil position change, and plate scale distortion.

9911-36, Session 8

An extensive coronagraphic simulation applied to LBT

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Coronagraphy is a widely adopted technique in current direct imaging instruments to address any scientific case that requires high contrast very close to a bright target, where diffraction usually prevents from achieving it. A coronagraph is characterized by a few key parameters: contrast, inner working angle, throughput and sensitivity to low-order aberrations. The large number of techniques currently known basically address in different ways the fundamental problem of the trade-off among them.

This article summarizes the results of a simulation program aimed at exploring different coronagraphic solutions for SHARK NIR, an instrument approved to proceed to the final design phase at Large Binocular Telescope. For the purpose, a dedicated simulation tool has been developed. The code is written in IDL language and makes use of the Physical Optics Propagation (POP) library PROPER. As a POP code, it performs propagation of electric field wavefronts through SHARK optical train according to scalar theory of diffraction, in an end-to-end fashion. The best Fresnel propagator at any position along the propagation axis is automatically selected by means of simultaneous propagation of a Gaussian pilot beam. The fully reflective design currently foreseen for the camera, as well as the absence of highly aspherical surfaces, make PROPER an optimal tool for the undergoing study.

The tool currently implements a set of coronagraphic techniques that have been identified as conceptually suitable for SHARK: from the classical Lyot and its variants (such as focal plane masks with Gaussian transmission profile in place of hard edge ones), to more advanced concepts such as Shaped Pupil or Apodized Lyot coronagraphs. However, any kind of technique can be easily implemented, with the only requirement of compatibility with the optical design.

As input, simulations use synthetic data-cubes of wavefront residuals after AO correction specifically generated for FLAO (the LBT XAO system) and corresponding to different values of seeing and guide star magnitudes, spanning a Strehl range going from ≥90% down to ≈30%. Optical aberrations not sensed by the AO system (NCPA) can be also introduced in a flexible way, via adjustable input parameters such as total amount in rms, power spectrum shape and temporal evolution law. The latter property is as critical as difficult to model, so particular attention has been dedicated to it.

Finally, the tool allows to generate multiple coronagraphic images in sequence, ready then to be processed by differential imaging pipelines (e.g. ADI) in order to compute ultimate detection limits of the camera in a given configuration. Real-time AO correction through the entire sequence ensures a realistic estimation of atmospheric speckles contribution to noise after post-processing (at the expense of computational time).

9911-37, Session 8

Measurement of vibration source amplitudes including a low-vibration centralized cryocooling system against the TMT AO performance vibration budget

Hugh A. Thompson, Douglas G. MacMartin, Thirty Meter Telescope (United States)

A key item element in the TMT AO image quality budget is an allocation of AO-corrected wavefront error to vibration (both image jitter due to relative motion of main optical elements and the effects of dynamic motion of individual primary mirror segments). This system allocation has been further subdivided into contributions from individual vibration sources at various locations in the TMT observatory both on and off the telescope. This vibration budget was allocated based on the results of finite element modelling of the system and guesses about the relative source strength of different vibrating equipment. Since that initial allocation, we have measured force amplitudes for a number of potential sources of vibration that may be installed at the TMT observatory. We report these results evaluating them against the specific frequency filter used in the TMT vibration budget. These include an evaluation of a range of possible cryocooling systems for the TMT instruments. These results help us to determine both the suitability of the equipment for TMT and the feasibility of our current vibration budget allocations.

9911-38, Session 8

Using frequency response functions to manage image degradation from equipment vibration in the Daniel K. Inouye Solar Telescope

William R. McBride II, National Solar Observatory (United States); Daniel R. McBride, Univ. of California, Davis (United States)

The Daniel K Inouye Solar Telescope (DKIST) will be the largest solar telescope in the world, providing a significant improvement in the resolution of solar images and magnetic field data available to the scientific community.

As with any large-aperture high-performance telescope, vibration of the telescope optics can degrade image quality. In fact, it is not unusual for this vibration to be the limiting factor in the resolution of a large telescope. Vibration mitigation is even more critical in long focal-length telescopes such as the Inouye Solar Telescope, especially when adaptive optics are employed to correct for atmospheric seeing.

An approach to managing this problem is described in the literature including the concept of a vibration error budget along with techniques to measure the mechanical transfer functions.

We have pieced together, from these and other sources, a method to quantify the transfer function, called the compliance frequency response function, between equipment mount points and telescope image motion. This method uses a large instrumented inertial-mass shaker to vibrate the telescope structure over a range of frequencies, while simultaneously using accelerometers to measure the response of the system at the mirror mounts (with dummy mirrors in place).

We then take the data, apply statistical and filtering methods for noise suppression and perform a discrete fast Fourier transform (FFT) to convert it to the frequency domain.

Using digital signal processing techniques, we estimate the transfer function between the shaker location and the various mirror mounts. Utilizing the sensitivity matrix from the telescope optical analysis, these displacements and rotations are transformed directly into units of image motion on the focal plane.

The results of these analyses are a set of frequency response functions between vibration source locations and image motion. These data are then used to determine the sensitivity of various locations in and around the telescope mount so that vibration error budgets can be established for each piece of equipment on the telescope mount.

This approach allows the DKIST engineers to design vibration-reducing solutions with accurate knowledge of the level of mitigation that must be achieved to realize the diffraction-limited image quality requirement.

Measurements were taken on the Inouye Solar Telescope mount assembly during the factory acceptance campaign. In this paper, we describe the data acquisition equipment, measurement approach, data analysis, results, and lessons learned.

9911-39, Session 8

Analysing the impact of vibrations on E-ELT primary segmented mirror

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The E-ELT primary mirror is 39m in diameter composed of 798 segments. It is exposed to external large but slow amplitude perturbations, mostly gravity, thermal and wind. These perturbations are efficiently rejected by a combination of edge sensor loop and adaptive optics (AO) in order to leave a small residual wavefront errors (WFE).

Vibrations induced by various equipment in the observatory are typically smaller amplitude but often higher frequency perturbations exceeding the rejection capabilities of these control loops. They generate both, low spatial frequency and high spatial frequency WFE. Especially segment phasing errors, i.e. high spatial frequency errors, cannot be compensated by AO. The effect of vibrations is characterized by excitation sources, transmission of the telescope structure and segment support, they all together define the WFE caused by M1 due to vibrations. It is important to build a proper vibration error budget and specification requirements from an early stage of the project.

This paper presents the vibration analysis and budgeting approach developed for E-ELT M1 and addresses the impact of vibrations onto WFE.

9911-40, Session 9

On the precision of aero-thermal simulations for TMT

Konstantinos Vogiatzis, Hugh A. Thompson, Thirty Meter Telescope (United States)

Environmental effects on the Image Quality (IQ) of the Thirty Meter Telescope (TMT) are estimated by aero-thermal numerical simulations. These simulations utilize Computational Fluid Dynamics (CFD) to estimate, among others, thermal (dome and mirror) seeing as well as wind jitter and blur. As the design matures, guidance obtained from these numerical experiments can influence significant cost-performance trade-offs and even component survivability.

The stochastic nature of environmental conditions results in the generation of a large computational solution matrix in order to statistically predict Observatory Performance. Moreover, the relative contribution of selected key subcomponents to IQ increases the parameter space and thus computational cost, while dictating a reduced prediction error bar.

The current study presents the strategy followed to minimize prediction time and computational resources, the subsequent physical and numerical limitations and finally the approach to mitigate the issues experienced. In particular, the paper describes a mesh-independence study, the effect of interpolation of CFD results on the TMT IQ metric, and an analysis of the sensitivity of IQ to certain important heat sources and geometric features.

9911-41, Session 9

Initial computational fluid dynamics modeling of the Giant Magellan Telescope site and enclosure

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In the era of extremely large telescopes (ELTs), with telescope apertures growing in size and tighter image quality requirements, maintaining a controlled observation environment is critical. This means that the geometry of the telescope's enclosure now plays an increasingly important role, thus requiring a more detailed understanding of how a proposed enclosure design will interact with the local wind microclimate on site.

Image quality is directly influenced by thermal gradients and the level of turbulence present in the incoming ambient air flow. Both of these factors decrease with height above grade, so a key function of any ELT enclosure is to minimize the infiltration of the ground layer air into the enclosure. Because wind forces on the telescope and its optics increase with the size of the telescope, a second key function of the enclosure of an ELT is to provide a means of modulating the velocity and direction of airflow through the enclosure and on the telescope. However, gaining an a priori

understanding of the wind environment's impacts on a proposed telescope can be challenging. It is complicated by the fact that telescopes are usually located in remote, mountainous areas. Such locations often do not have high quality historic records of the wind conditions, and can be subject to highly complex flow patterns that may not be well represented by the traditional analytic approaches used in the design of typical buildings.

As part of the design process for the planned Giant Magellan Telescope (GMT) at Cerro Las Campanas, Chile; the authors have conducted parametric design study to assess how the telescope's position on the leveled mesa, its ventilation configuration and the design of the enclosure and windscreens could be optimized to minimize the infiltration of grade level ambient air. The study consisted of several dozen computational fluid dynamics (CFD) simulations. These simulations initially investigated the wind microclimate on the mesa under existing conditions to understand the naturally occurring variations in wind flows across the site. Further simulations were then conducted of two enclosure concepts with various enclosure venting and windscreen options employed, at three locations on the mesa. The air flow rates into the telescope enclosure from each of the simulations was then predicted and compared. This comparative data set was then used to inform decision making related to the design and siting of the GMT.

9911-42, Session 9

Site and enclosure CFD modeling and analysis for the Giant Magellan Telescope

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The Giant Magellan Telescope (GMT) is currently planned for construction at a summit at the Las Campanas Observatory (LCO) in Chile. As one of the next generation of extremely large telescopes (ELTs), GMT will be one of the most powerful ground-based telescope in operation in the world. Due to the larger aperture envisioned for GMT, characterization and control of the air flow entering and circulating within the enclosure will be required to maintain the highest possible image quality. Aero-thermal interactions between the site topography, enclosure, internal systems, and optics are complex. A key parameter for optical quality is the thermal gradient between the terrain and the air mass entering the enclosure, and how quickly that gradient can be dissipated to equilibrium. Because the thermal gradients are highest near the ground, an important function of the GMT enclosure is to minimize the flow of ground-layer air entering the enclosure. Moreover, the enclosure must also provide a means to modulate the magnitude and direction of the flow velocity on the telescope optical system to minimize wind loading and vibration. Thus, to ensure the highest quality GMT optical performance, computational fluid dynamics (CFD) models and specialized analyses are utilized to examine airflow over the leveled mesa on the peak at LCO, the airflow conditions around two GMT enclosure concepts located at three possible sites on the summit mesa, and the impacts of enclosure soffit geometry, ventilation configurations, and windscreens on airflow through the telescope and enclosure.

High-fidelity Reynolds-Averaged Navier Stokes (RANS) CFD analysis of the GMT, enclosure, and LCO terrain is performed using the Ansys Fluent software package. In this work, CFD is used to specifically study (a) the impact of either an open or closed enclosure base soffit external shape design, (b) the effect of telescope/enclosure location on the mountain summit, and (c) the effect of enclosure venting patterns and windscreens on the airflow entering the enclosure. In the final paper, details on geometry modeling of the GMT telescope, enclosure, and LCO terrain, and associated unstructured mesh discretization are first described. Then, results from a set of flow solutions are shown to quantify the quality of the airflow entering the GMT enclosure based on soffit, site location, and venting and windscreen considerations. Based on the results, conclusions on GMT soffit design, site location, and enclosure venting will be discussed and presented.

9911-43, Session 9

Thermal control modeling approach for GRAPE (GRAntecan PolarimEter)

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GRAPE is the polarimeter planned to be installed on the main Cassegrain focus of GTC (Gran Telescopio Canarias), having an equivalent entrance pupil of 10.4 m, located at the Observatorio del Roque de los Muchachos , in La Palma, Canary Islands. It's meant to deliver full Stokes (IQUV) polarimetry covering the spectral range 0.420-1.6 um, in order to feed the HORS instrument (High Optical Resolution Spectrograph), mounted on the Nasmyth platform, which has a FWHM resolving power of about 25,000 (5 pixel) designed for the wavelength range of 380-800 nm. Two calcite blocks and a BK-7 prism arranged in a Foster configuration are splitting the Ø12.5mm collimated beam into the ordinary and extraordinary components. The entire subunit from the Foster prisms down to the input fibers is rotated by steps of 45 degrees in order to retrieve Q, U components. By inserting a quarter wave retarder plate before the entrance to the Foster unit circular polarization is measured too.

The current paper consist of two main parts: at first thermal analysis simulations are introduced, which have been run compliant to the specifications derived by the environmental conditions and the transient thermal gradients (°C/h) taking into account the motors and lamps installed; then a thermal control model is proposed to minimize the image quality degradation at different exposure times when compensation via passive insulation is not enough. The tools deployed to achieve such goal are the ANSYS Multiphysics and Fluent package, Zemax and several Python/Matlab scripts to import into Zemax the surface motions and the different refractive indices values depending on the temperature distribution.

9911-44, Session 9

Improvements in optomechanical analysis techniques for segmented mirror arrays

Gregory J. Michels, Victor L. Genberg, Gary R. Bisson, Sigmadyne, Inc. (United States)

The employment of actively controlled segmented mirror architectures has become increasingly common in the development of current astronomical telescopes. Optomechanical analysis of such hardware presents unique issues as compared to that of monolithic mirror designs. The work presented here is a review of current capabilities and improvements in the methodology of the analysis of mechanically induced surface deformation of such systems. The recent improvements include capability to differentiate surface deformation at the array and segment level. This differentiation allowing surface deformation analysis at each individual segment level offers useful insight into the mechanical behavior of the segments that is unavailable by analysis solely at the parent array level. In addition, capability to characterize the full displacement vector deformation of collections of points allows analysis of mechanical disturbance predictions of assembly interfaces relative to other assembly interfaces. This capability, called racking analysis, allows engineers to develop designs for segment-to-segment phasing performance in assembly integration, 0g release, and thermal stability of operation. The performance predicted by racking has the advantage of being comparable to the measurements used in assembly of hardware. Approaches to all of the above issues are presented and demonstrated by example with SigFit, a commercially available tool integrating mechanical analysis with optical analysis.

9911-45, Session 10

End-to-end (E2E) simulations for small space telescopes: a case study

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Large astronomical missions are usually general-purpose telescopes with a suite of instruments optimized for different wavelength regions, spectral resolutions, etc. Their E2E simulations are typically photons-in to flux-out calculations made to verify that each instrument meets its performance specifications. In contrast, smaller space missions are usually single-purpose telescopes, and their E2E simulations start with the scientific question to be answered and end with an assessment of the effectiveness of the mission in answering the question. Thus, E2E simulations for small mission concepts are broader in scope than for large missions, as they include not only the telescope and instrumentation, but also the spacecraft, orbit, and external factors such as coordination with other telescopes. We will illustrate the strategy and organization of small-mission E2E simulations using the Galaxy Evolution Spectroscopic Explorer (GESE) as a case study. GESE is an Explorer/Probe-class space mission concept with the primary aim of answering the scientific question of why star formation in galaxies started to decline after reaching a peak when the universe was only 3 billion years old and continues to decline to this day.

9911-46, Session 10

An integrated modeling framework for the Large Synoptic Survey Telescope (LSST)

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All of the components of the LSST subsystems (Telescope and Site, Camera, and Data Management) are in production, either by vendors or by in-house engineering teams. The major systems engineering challenges in this early construction phase are establishing the final technical details of the observatory, and properly evaluating the change and deviation requests due to financial and technical constraints emerging from the detailed design and manufacturing process. To meet these challenges, the LSST Project Systems Engineering team established an Integrated Modeling (IM) framework including (i) a high fidelity optical model of the observatory, (ii) an atmospheric aberration model, and (ii) perturbation interfaces capable of accounting for quasi static and dynamic variations of the optical train. The IM can also be coupled to a comprehensive astronomical sky model, making it feasible to image individual bright or faint stars (point sources), or generating a fully populated focal plane image with stars and galaxies.

The model described is integrated in the sense that it constitutes a joint simulation of optics, structure, and control in an integrated fashion. This integrated model supports the periodic evaluation of two key LSST Measures of Performance: image quality and ellipticity, i.e. the size and shape of the system PSF across the 3.5 degrees field of view. Image quality is characterized by two connected, but not equivalent metrics: the (i) real FWHM of the PSF, and the (ii) effective FWHM characterizing the background limited photometric depth (detection limit) of the system. The latter one is equivalent to the system Point Source Sensitivity (PSSN), relating the expected photometric depth to the absolute atmospheric detection limit.

At the front end, the IM is linked to environmental and operational parameters, as well as to the structural and thermal finite element models of the system. Manufacturing, assembly, and alignment tolerances are included, together with the open loop (LUT) corrections and compensations for these errors. Furthermore, the feedback loops utilizing mechanical (encoder) and thermal sensors, and optical (guider and WFS) information can be investigated by the tools developed.

The paper will include actual examples for applying the established framework. LSST has four curvature wavefront sensors to monitor and control its image quality. In a recent trade study, the separation of their intra and extra focal images was optimized by applying the high fidelity optical and atmospheric IM tools. The envisioned control strategy for the LSST Active Optics System (AOS) was verified by extensive simulations in the presence of the expected atmosphere and system perturbations. A brief summary of the methods and results will demonstrate the comprehensive nature of the framework. Finally, the investigation of the feasibility of additional structural dampers will be reported, as an example for the dynamic application of the tool.

9911-47, Session 10

Science yield modeling with EXOSIMS

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Estimating the science yield of a space mission constitutes an essential way of selecting and refining the most appropriate technologies or instruments. In the case of an exoplanet imaging mission, it identifies specification cases likely leading to zero detections, and allows avoiding a worst case scenario. The Exoplanet Open-Source Imaging Mission Simulator (EXOSIMS) is designed to allow for systematic exploration of expected science yields over the course of a specific mission, and is currently being developed as part of the WFIRST-AFTA Preparatory Science investigation. Here, we report on our ongoing development of EXOSIMS and mission simulation results for WFIRST-AFTA. We present the interface control and the modular structure of the software, along with corresponding prototypes and class definitions for each of the modules, e.g. planet population, star catalog, optical system, background sources, post-processing, etc. This modular structure allows users to investigate multiple missions or system designs by only modifying individual modules without having to redefine the unaffected ones. More specifically, we also provide a full set of modules dedicated to WFIRST-AFTA. In that context, we show and discuss the results of some preliminary WFIRST-AFTA simulation ensembles, i.e. collections of a large number of survey simulations, using different envisioned coronagraph instruments. We focus on simulating a mission using both the Hybrid Lyot Coronagraph (HLC) and the Shaped Pupil Coronagraph (SPC) for detection and characterization, respectively. The analysis of such simulation ensembles leads to decisive conclusions regarding the coronagraph instrument operation, such as (i) optimal target selection, (ii) optimal time spent on imaging known planets vs. detecting new ones, (iii) optimal operating points in terms of detection band. EXOSIMS will continue to be further developed through the final release in May of 2017, and will be used to continuously refine the modeling of the WFIRST-AFTA coronagraph science.

9911-48, Session 10

Structural, thermal, and optical performance (STOP) modeling and results for the James Webb Space Telescope integrated science instrument module

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The James Webb Space Telescope (JWST) is a general astrophysics mission which consists of a 6.6m diameter, segmented, deployable telescope for cryogenic IR space astronomy (~40K). The JWST Observatory architecture includes the Optical Telescope Element and the Integrated Science Instrument Module (ISIM) element. ISIM contains four science instruments (SI) and a Guider mounted to a composite metering structure. ISIM is optically tested at NASA Goddard Space Flight Center using a telescope simulator (Optical telescope element SIMulator; OSIM). OSIM is a high-fidelity, cryogenic JWST telescope simulator that features a ~1.5m diameter powered mirror.

We performed extensive Structural, Thermal, and Optical Performance (STOP) modeling in support of all phases of ISIM development. In this paper, we focus on modeling and results associated with test and verification. While ISIM's ground testing is comprehensive, a perfect, on-orbit test environment does not exist or would be difficult to create (e.g., 0-g effects, flight-like thermal gradients). We used STOP modeling to predict system performance in 0g and various temperature environments. The on-orbit predictions are used to translate ground test results to on-orbit performance. We used tests to validate our models (i.e., g-release, co-boresight, and jitter testing) to build confidence in our predictions for on-orbit performance.

The integrated STOP model is composed of structural, thermal and optical models. The OSIM and SI teams developed structural (i.e., finite element model; FEM) and optical (i.e., ray trace) models that were delivered to ISIM. We developed NASTRAN, CodeV, and Thermal Desktop models of ISIM's composite metering structure, OSIM, and other test equipment. We defined and added six degree of freedom reference "nodes" to the structural and optical models. The nodes were located at the critical opto-mechanical positions. The structural models were offset by the changes induced by thermal changes and the resultant node offsets were used to alter the optical models and predict performance.

STOP analysis started early in the JWST program and its role evolved. For example, the nodes were initially set prior to SI integration and test. As the SIs progressed through their builds, the models were updated to represent as-built locations. Each SI model delivery was tracked through configuration management and the STOP models were revised and tracked.

We report the STOP analysis results used for g-release, jitter, co-boresight, boresight, pupil shear/roll, wavefront error, and focus, including the alignment mechanism offsets needed to account for ground to orbit changes. Early in the development of the ISIM ground test program, we used this analysis to understand the impact of the cryogenic test environment on these parameters. For example, ISIM has a co-boresight alignment requirement that is challenging to measure via test. We used STOP analysis to design the co-boresight test and predict the output. After the test was complete, we used the results to validate the STOP model. Similarly, an ambient g-release test was performed on ISIM using metrology, validating the structural model. These validation tests were a check against possible workmanship errors that might contribute to systematic error in our on-orbit performance predictions.

9911-49, Session 10

Exploring possible Large Synoptic Survey Telescope (LSST) surveys with the LSST operations simulator and delivering a reference simulated survey

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The operation simulator (OpSim) for the Large Synoptic Survey Telescope (LSST) models the sequences of observations that might be undertaken by the survey given the properties of the site, telescope and camera, and the science goals of the project. OpSim simulations have been used to inform the LSST site selection process and drove the move from the originally proposed 3 degree field-of-view to the current 3.5 degrees. OpSim simulations have also been used to optimize mechanical specifications of the LSST including various motor power capabilities, heat dissipation and cable wrap details. OpSim reads database tables for cloud cover and seeing, calculates sky brightness values across the sky and references internal science proposals which request observations under conditions appropriate to the science case. The requested observations are weighted with relatively simple algorithms and the most highly valued observation is taken. There is no look-ahead and this algorithm is commonly described as a 'greedy' algorithm (see Delgado et. al. SPIE_9150-39 for more details). All aspects of an observation are saved in MySQL database tables. The output is analyzed using a custom tool, the Metrics Analysis Framework (MAF). Two sets of metrics are typically run on a simulation's output, one focussing on the performance and behavior of OpSim and another set focussing on a science analysis.

Recent simulations have focussed on exploring different science proposal sets and science proposal parameters. There are two basic types of science proposals, time domain and area, with a wide range of variations within each depending upon the values of hundreds of parameters. The key proposal is the Wide Fast Deep proposal (WFD) which attempts to collect 18,000 square degrees with 825 visits to each field in 10 years in sets to optimize NEO detection. This proposal meets a primary design goal of the LSST Science Requirements Document. The requested WFD observations leave about 20% of the 10 year survey available for other proposal. The main non-WFD proposals we have been investigating cover the Milky Way plane, the South Celestial Pole, the region of the ecliptic north of the WFD area and various sets of fields with intense sampling (Deep Drilling fields) for depth and time sampling.

We present the MAF analyses (which are available via web browser) of a set of simulations exploring various combinations of these proposals as well as variations in parameters governing the proposals (eg airmass, seeing, sky brightness limits). These runs are available to the community for analyses specific to a particular investigator's interests. Both MAF and OpSim are publicly available.

Finally, we describe the 2015 baseline LSST survey simulation, the assumptions that go into this simulation, and the resulting observational characteristics of such a survey. In subsequent years, we expect to publish updated baselines as we better understand the properties of the delivered LSST system, the response of the science to different observing strategies, and enhancements in the algorithms used to schedule the telescope.

9911-50, Session 10

Creating the right atmosphere: analyzing extensive telemetry data to create more realistic, computationally efficient atmosphere models for end-to-end simulations

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End-to-end simulation of the next generation of telescopes, their adaptive optics systems, instrumentation, and control systems is a necessity given their high cost and complexity. Underpinning all simulations is the atmosphere model through which wavefronts from artificial (i.e. simulated) sources accumulate phase errors and are then propagated through a representation of the telescope's optics to observe the effect on the system's point spread function (PSF). At the level of detail required for error budgets in large, complex systems standard assumptions like Kolmogorov (or von Karman) turbulence and Taylor frozen flow are no longer adequate representations of reality. In our prior work we have demonstrated that adding even small amounts of "boiling" to atmosphere models results in drastic degradations in figures of merit such as contrast ratio for direct exoplanetary imagers (like the Gemini Planetary Imager (GPI)) or PSF spatial variability for wide field telescopes (e.g. Large Synoptic Survey Telescope or LSST). GPI attributes a four-fold increase in on-sky bandwidth error versus estimated performance to simplistic atmosphere models used in simulations.

Using an autoregressive (AR) model to fit extensive telemetry data gathered by GPI and the ShaneAO system at Lick Observatory, we demonstrate the utility of an atmospheric model with multiple degrees of freedom to match real-world conditions. Phase screens generated using the AR method have power spectral densities (PSD) tailored to match measured PSDs, incorporate stochastic content at each time step to simulate "boiling", accommodate multiple wind layers of varying wind velocity and direction, set statistical parameters like coherence length (r0) and outer scale (L0) for each wind layer, and evolve them in time in a manner consistent with measured data. By operating primarily in the Fourier domain, this model creates realizations of phase screens that are computationally efficient and sparing in their use of memory, thus enabling simulations of long exposures, telescopes with large apertures or wide fields of view. The addition of stochastic content at each timestep also mitigates periodicity issues associated with sample-based phase screen generation methods. The method is simple to implement in any optical simulation environment and source code is readily available and freely licensed for immediate use. It has extended the capabilities of the GPI adaptive optics simulator by enabling long-exposure simulations that model the effect of slow time-varying aberrations. LSST simulations exploit the AR method's memory efficiency to reduce the size of phase screens used and the ability to introduce stochastic variations to observe their effect on PSF stability.

Conference 9912: Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation

Sunday - Friday 26–1 July 2016

Part of Proceedings of SPIE Vol. 9912 Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation II

9912-1, Session 1

A prototype of the NFIRAOS to instrument thermo-mechanical interface

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The Narrow Field InfraRed Adaptive Optics System (NFIRAOS) is the first-light facility Adaptive Optics (AO) system for the Thirty Meter Telescope (TMT), located on the Nasmyth platform. NFIRAOS accepts light from the telescope, corrects it and selectively feeds it to a collection of client instruments at dedicated instrument ports, including planned science instruments: IRIS and IRMS. NFIRAOS optical components are maintained in a controlled cold environment; the NFIRAOS enclosure provides this function by using a refrigeration system embedded in its walls to intercept heat from its surroundings. NFIRAOS also includes three sealed instrument interface ports.

In order to meet the optical performance and stability specifications, all of the optical components within NFIRAOS are protected within the large enclosure maintained at -30°C ± 0.5°C, as well as staying clean and dry. The walls of the enclosure consist of thermally insulated panels with actively cooled aluminum thermal conduction plates to intercept the heat flux from the environment. Three of the insulated panels are modified to be used as dedicated instrument ports. Instruments are not permitted to disrupt the internal environment of the NFIRAOS enclosure. This is complicated by the fact that NFIRAOS and the instruments do not have a window to separate them and because instruments rotate with respect to NFIRAOS on a large mechanism. Sealing from the external TMT environment at this interface is accomplished using a set of rotating seals. Additionally, due to long warm-up and cool-down times for NFIRAOS, the instruments must be installed and removed while at -30°C without allowing any influx of warm, humid, dirty air creating concerns about humidity/frost and contamination during instrument changes. It was decided that a prototype of both the instrument interface and the enclosure wall panel would be a cost-effective risk reduction strategy.

The prototyping activity was separated into two stages. The first stage was to build one section of the enclosure wall, integrate it into an existing freezer room and assess performance and manufacturability. Temperature homogeneity was measured over the length of the wall panel while freezer simulated the internal NFIRAOS environment. Temperature stability over time was also measured. The second stage of activity was to build the instrument side of the interface and test for temperature stability (of the rotating seal), frost accumulation and the instrument change process. Of particular interest was to find out whether rotating seals in the interface would leak or freeze. Issues have been identified which are being flowed into the final design of the enclosure and the interface to the instruments. For example, while testing for frost accumulation, it was determined that there needs to be a localized re-heat cycle at the instrument port to avoid frost build-up on the NFIRAOS side of the interface.

Enclosure prototyping effort has been performed to reduce risk and identify design, operational and manufacturing issues. One wall panel of the actively cooled enclosure and a half-scale version of the instrument interface have been prototyped at NRC-Herzberg. Results of testing and lessons learned from prototyping are presented here.

9912-2, Session 1

Polarization dOTF: on-sky focal plane wavefront sensing

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Differential Optical Transfer Function (dOTF) is a focal plane wavefront sensing method that uses a diversity in the pupil plane to generate two different focal plane images. The difference of their Fourier transforms recovers the complex amplitude of the pupil to the spatial scale of the diversity. We produce two simultaneous PSF images with diversity using a polarizing filter at the edge of the telescope pupil, and a Polarization Camera to simultaneously record the two images. Here we present the first on-sky demonstration of polarization dOTF at the 1.0m South African Astronomical Observatory telescope in Sutherland, and our attempt to validate it with simultaneous Shack-Hartmann wavefront sensor images.

9912-3, Session 1

Electromagnetic deformable mirror development at TNO

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Modern astronomy often relies on adaptive optics to improve the overall imaging performance, utilizing a deformable mirror (DM) to compensate for aberrations stemming from for instance turbulences in the atmosphere. Over the last decade TNO developed a deformable mirror concept using electromagnetic actuators with the main advantages of having very low non-linearity and hysteresis, low power consumption, and the inherent high reliability of these actuators. The latter is due to the fact that the electromagnetic actuators do not suffer from any material aging or depolarization.

TNO recently started a program to redesign the electromagnetic actuator to improve the actuator efficiency, allowing higher actuator force per volume and per unit electrical power. This is achieved by changing the actuator configuration to allow separated flux paths between the driving coil and permanent magnets used to pre-magnetize the circuit. The resulting DM design is highly scalable, with an actuator pitch from 4mm up to more than 30mm. The increased actuator efficiency can be utilized to further optimize the behavior of the deformable mirror depending in the target application. By tuning the stiffness of the actuator structure an optimal balance can be found between dynamical performance, actuation range, and power dissipation.

Another major advantages of the newly developed actuator configuration is that it allows relatively straightforward refurbishment of the mirror membrane without the need for completely dismantling the actuator structure. This will reduce the overall operating cost and risks at for the end user.

With this technology various applications in the fields of ground-based

astronomy can be targeted, and also for space missions, including both earth observation and science missions. Especially for such highly costly and critical missions, the reliability and low-power consumption of the novel DM design are considered main assets. A separate design study is conducted to evaluate and improve the DM design for the space environment.

In order to validate the actuator performance several actuator breadboards are being built and tested, demonstrating the improved actuator response. In this paper the concept of the newly developed electromagnetic DM will be explained, the results from the actuator tests will be presented, and an outlook will be given on the development of the improved electromagnetic DM concept.

9912-4, Session 1

NFIRAOS beam splitters subsystems optomechanical design

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The early-light facility adaptive optics system for the Thirty Meter Telescope (TMT) is the Narrow-Field InfraRed Adaptive Optics System (NFIRAOS). The science beamsplitter changer mechanism and the visible light beamsplitter are subsystems of NFIRAOS. The beamsplitter changer mechanism allows selection between the science beamsplitter and an engineering beamsplitter for use with the high-resolution wavefront sensor (HRWFS) during system integration. The visible light beamsplitter divides the visible light in two paths, one for the Natural Guide Star (NGS) wavefront sensor (WFS) and another for the Laser Guide Star (LGS) WFS.

This paper presents the optomechanical design of the beamsplitters subsystems. Also, the integrated optomechanical analysis approach used to evaluate the optical performance of the mounted beamsplitters under environmental constraints is detailed.

First, the transmitted and reflected wavefront error of the beamsplitters must be kept as low as possible. The size and weight of the optical components coupled with the low operating temperature of -30°C represents a challenge for the mounting strategy. Special care is taken to deal with the coefficient of thermal expansion (CTE) mismatch between the fused silica beamsplitters and the steel table structure. Also, the mass budget allowed for the science and engineering beamsplitter changer mechanism requires optimization to ensure compliance with the minimum natural frequency, handling acceleration and seismic requirements. Finally, tip/tilt alignment and positional stability over time also influence the optomechanical design solutions.

The selected mounting method for the beamsplitters uses room temperature vulcanizing (RTV) adhesive to bond each beamsplitter in its respective steel cell. The high CTE of the RTV allows to compensate for the CTE mismatch between the fused silica beamsplitters and the steel cell. The beamsplitters are bonded with RTV dots that are optimized in terms of quantity, diameter and thickness in order to minimize the WFE while maximizing the natural frequency. This mounting approach allows to use steel for all mechanical parts, providing an assembly with matched CTE from the optical cell to the table structure. This simple design imparts very low optical surface deformation on the beamsplitters and has the advantage to avoid the use of invar and flexures, which are more expensive.

A finite element model using Ansys is developed to optimize the design and to verify that all the requirements are met. In addition to the modal and the structural analyses, the beamsplitter surface deformations are computed considering the environmental constraints during operation. Surface deformations are fit to Zernikes polynomials using SigFit software. Rigid body motion as well as residual RMS and peak to valley surface deformations are calculated. Finally, deformed surfaces are exported to Zemax to evaluate transmitted and reflected wavefront error. The simulation results of this integrated optomechanical analysis have shown compliance with all optical requirements.

9912-5, Session 2

Development and test of the Ball Aerospace optical frequency comb: a versatile measurement tool for aerospace applications

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The Ball Fiber Optical Comb Demo is a lab-based system which is used to develop space applications for optical frequency combs. These developments utilize the broadband optical coherence of the frequency comb to expand the capabilities of ground test and orbital systems used for optical wave-front measurement, control of adaptive optics, precision ranging, and reference frequency stabilization. The development expands upon a NIST-developed all-fiber frequency comb that exhibits high stability in a compact, enclosed package.

Previously demonstrated applications for frequency combs, include: spectroscopy, distance and velocity measurement, frequency conversion, and timing transfer. Results from the Ball system show the characterization and performance of a frequency comb system with a technological path-to-space. Demonstrations in high precision metrology and long-distance ranging are also presented for application in adaptive and multi-body optical systems.

9912-6, Session 2

A soft actuator for prototype segmented mirror telescope

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Segmented mirror telescopes (SMT) are built using small hexagonal mirror segments placed side by side so that it works like a monolithic mirror of very large size. Optical figure of such a segmented primary mirror need to be maintained against external disturbances introduced by gravity, temperature, wind as well as structural vibration. This very important task is done by the three position actuators combined with six edge sensors per segment working at few nano-meter scale. In this paper we describe our effort to develop a force/position soft actuator for a Prototype Segmented Mirror Telescope (PSMT), under development in Indian Institute of Astrophysics, Bangalore. PSMT is a 1.3m effective diameter, seven segment test bed telescope which requires twenty one precision actuators. Our actuator is a compact, light weight, soft actuator, uses similar technology adopted in upcoming extremely large telescopes like TMT and E-ELT. We have chosen soft actuator, because it is subjected to low mechanical losses and provide high bandwidth with the ability to correct wind and vibration disturbances. The prime mover of our actuator is a Voice Coil Motor (VCM) which takes care of dynamic load on the actuator and generates required force to correct for disturbances. VCM combined with high resolution linear position encoder provides very accurate positioning ability. The output shaft of actuator is isolated from its rigid frame with the help of a

Disc Spiral Flexures (DSF) made of very thin metallic discs. This actuator also consist of an offloading mechanism which in turn offloads the static load on VCM to reduce the overall power consumption. Although, almost all components required for the actuator are custom design and built, however, we put our best efforts to minimize the production cost as much as possible and made it affordable for the PSMT which is relatively low budget project.

The VCM and DSF are designed using numerical simulation and FEM analysis technique. Detailed control analysis has also been carried out to understand the performance of the actuator in different conditions i.e. closed loop, open loop, with and without external disturbance. Based on results obtained from simulation and parametric sensitivity analysis, stable design parameters are obtained and used in the mechanical design. The actuator is designed to provide the output stroke of 2.5mm and the track rate of 324nm/s (6.5mN/s) with tracking accuracy better than 25nm. In addition to these it is also expected to have high reliability and long life. In this paper we describe electromechanical design aspects of the device and provide details on our works carried out toward modelling and simulation. Finally we present preliminary experimental results obtained from prototype actuator developed for the PSMT.

9912-7, Session 2

ZERODUR strength modeling with Weibull statistical distributions

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The decisive influence on breakage strength of brittle materials such as the low expansion glass ceramic ZERODUR® is the surface condition. For polished or etched surfaces it is essential if micro cracks are present and how deep they are. Ground surfaces have many micro cracks caused by the generation process. Here only the depths of the micro cracks are relevant. In any case presence and depths of micro cracks are statistical by nature.

The Weibull distribution is the model used traditionally for the representation of such data sets. It is based on the weakest link ansatz. The use of the two or three parameter Weibull distribution for data representation and reliability prediction depends on the underlying crack generation mechanisms. Before choosing the model for a specific evaluation, some checks should be done. Is there only one mechanism present or is it to be expected that an additional mechanism might contribute deviating results? For ground surfaces the main mechanism is the diamond grains' action on the surface. However, grains breaking from their bonding might be moved by the tool across the surface introducing a slightly deeper crack. It is not to be expected that these scratches follow the same statistical distribution as the grinding process. Hence, their description with the same distribution parameters is not adequate. Before including them a dedicated discussion should be performed.

If there is additional information available influencing the selection of the model, for example the existence of a maximum crack depth, this should be taken into account also. Micro cracks introduced by small diamond grains on tools working with limited forces cannot be arbitrarily deep. For data obtained with such surfaces the existence of a threshold breakage stress should be part of the hypothesis. This leads to the use of the three parameter Weibull distribution. A differentiation based on the data set alone without preexisting information is possible but requires a large data set. With only 20 specimens per sample such differentiation is not possible. This requires 100 specimens per set, the more the better.

The validity of the statistical evaluation methods is discussed with several examples. These considerations are of special importance because of their consequences on the prognosis methods and results. Especially the use of the two parameter Weibull distribution for high strength surfaces has led to non-realistic results. Extrapolation down to low acceptable probability of failure covers a wide range without data points existing and is mainly influenced by the slope determined by the high strength specimens. In the past this misconception has prevented the use of brittle materials for stress loads, which they could have endured easily.

9912-8, Session 2

Development and final design of the FAME active array

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FAME (Freeform Active Mirror Experiment - part of the FP7 OPTICON/FP7 development programme) intends to demonstrate the huge potential of active mirrors and freeform optical surfaces that can help to address the new challenges of next generation astronomical instruments, which are bigger, more complex and have tighter specifications than their predecessors.

The FAME design consists of a pre-formed, deformable thin mirror sheet with an active support system. The thin face sheet provides a close to final surface shape with very high surface quality. The active array provides the support, and through actuation, the control to achieve final surface shape accuracy.

In the current paper the development path, trade-offs and demonstrator design of the active array of FAME is presented. The key steps of the development process of the active array are the design of the mechanical structure and especially the optimization of the actuation node positions, where the actuator force is transmitted to the thin mirror sheet. This is crucial for the final performance of the mirror where the aim is to achieve accurate surface shapes, with low residual (high order) errors using the minimum number of actuators. The activities are based on the coupling of optical and mechanical engineering, by using analytical and numerical methods, which results an active array with optimized node and surface shape design.

The research of the design and development of a special actuator and control for FAME can be found in the paper "Thermal expansion used as a precision actuator" of this conference.

9912-9, Session 2

Stressed mirror anular polishing for scale-down TMT segments

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A new Stressed Mirror Polishing technology carried out on Annular polishing machine has been developed in NIAOT. Since three or more pieces of segments can be polished simultaneously on one annular polishing machine, this SMAP technology will provide higher efficiency for massive production of Off-axis segments of the extremely large telescope. With the help of a 3.6m in diameter annular polishing machine, two scale-down TMT segments have been polished using SMAP technology. Both of two segments are 1100 mm in diameter, with the radius of curvature of 60 m in the vertex and aspheric constant K=-1.000953. The off-axis distance is 8 m and 12 m respectively. After SMAP the reasonable surface accuracy is reached. The final surface accuracy is 1.12 mm PV, 0.23 mm RMS for OAD 8m segment, and 1.22 mm PV, 0.26 mm RMS for OAD 12m segment.

9912-10, Session 2

Research on key issues of large diameter off-axis aspheric segments testing

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The research works are summarized on 1.1m off-axis aspheric segments which are scaled-down TMT segments polished by NIAOT using SMAP (Stressed Mirror Annular Polishing) method in the previous phase and testing preparations for 1.45m mirrors. The detailed introduction is given on result of errors analysis in contact detection testing of segments. Those errors include supporting deformation caused by gravitation, detection error of reference mirror counting in interference testing by temperature gradients of air and corresponding restrain measurements, mirror alignment error in contact detection, simulation and statistics on random error of length gauges. In the second part, the selected basis of sampling number for contact-type detector arrays and the terms number of Zernike polynomials we need are studied. And the situations on orthogonality destruction of Zernike polynomials in discrete points sampling case and spectral analysis for each order Spherical aberrations in continuous sampling are introduced. Next, the selection strategy and the results of unified best-fitting sphere for dozens segments which may be processed are presented. Finally, a brief introduction is made on detection system for 1.45m segments being installed at the present stage.

9912-11, Session 3

Diamond machining of large ZnSe grisms for the Rapid Infrared/Imager Spectrograph (RIMAS)

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The Rapid Infrared Imager/Spectrograph (RIMAS) is an instrument designed to observe gamma ray burst afterglows following initial detection by the SWIFT satellite. Operating in the near infrared between 0.9 and 2.4 μm, it has capabilities for both low resolution (R~25) and moderate resolution (R~4000) spectroscopy. Dispersion in the moderate resolution mode is provided by a pair ZnSe grisms: one covering the Y and J bands and the other covering the H and K. Each has a clear aperture of 40 mm. The YJ grism has a blaze angle of 42.8º and a periodicity of 25 lines/mm. For the HK grisms the blaze is 57º with a 20 line/mm periodicity.

The grisms are being diamond machined on the Precision Engineering Research Lathe (PERL) at LLNL. Details of the fabrication and results of optical testing will be reported.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

9912-12, Session 3

Polishing techniques for MEGARA optics

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MEGARA (Multi-Espectrógrafo en GTC de Alta Resolución para Astronomía) is the new integral-field and multi-object optical spectrograph for the 10.4m Gran Telescopio Canarias, now under the construction. It will offer spectral resolutions in the range of R=6000-20000.The dispersive elements are volume phase holographic (VPH) gratings, sandwiched between two flat Fused Silica windows of high optical precision in large apertures. The design, based in VPHs in combination with prisms made of Ohara PBM2Y optical glass allows to keep the collimator and camera angle fixed. Seventy three optical elements are being built in Mexico at INAOE and CIO. For the low resolution modes, the VPHs windows specifications in irregularity is 1 fringe in 210mm x 170mm and 0.5 fringe in 190mm x 160mm for a window thickness of 30mm. For the medium and high resolution modes the irregularity specification is 2 fringes in 220mm x 180mm and 1 fringe in 205mm x 160mm for a window thickness of 20mm. In this work we present a description of the polishing techniques developed at INAOE optical workshop to manufacture the 36 Fused Silica windows and 24 PBM2Y prisms that allows us to achieve such demanding specifications. We include the processes of mounting, cutting, blocking, polishing and optical interferometric testing.

9912-13, Session 3

A large size ion beam figuring system for 1.2m astronomical telescopes fabrication

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A large ion beam figuring system has been build to figure large size optics with maximum dimensions of 2.0?2.0?0.6m at National University of Defense Technology (NUDT) in China. This system can realize five-axial motion of ion resource. This paper main introduce how to machine a 1.2m SiC optics using this IBF system, which includes different ion grids selection of ion source, dwell time algorithm and scan path planning etc. The final figuring contour accuracy is 9nm.

9912-14, Session 3

Manufacturing of super-polished large aspheric/freeform optics

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Very large optical systems targeting diffraction-limited high spatial resolution and/or more light collecting efficiency have been increasingly popular in advanced optical system concepts and designs such as Giant Magellan Telescope and Large Synoptic Survey Telescope. Number of next generation astronomical telescopes or large optical systems utilize aspheric/freeform optics since they enable segmented optical system creating a combined large optical surface or off-axis optical design avoiding obscurations, which could be a source of stray-light noise. For instance, in order to avoid light scattering from the secondary mirror structure, the Daniel K. Inouye Solar Telescope (DKIST) adopts a 4.2 m in diameter off-axis primary mirror using Zerodur thin substrate. The DKIST primary mirror has been successfully completed in 2015 at the Optical

Engineering and Fabrication Facility (OEFF), University of Arizona. As the telescope looks at the brightest object in astronomy, our own Sun, the primary mirror surface quality needs to meet comprehensive and extreme specifications. While most optical systems often have only two major specifications defining i) low spatial frequency error (e.g. overall optical surface figure error RMS) and ii) very high spatial frequency error (e.g. surface finish within 1 by 1 mm local area) the DKIST optical surface specification covers broad range of surface error spectrum in terms of the overall surface error, bidirectional reflectance distribution function (BRDF) associated with its power spectral density (PSD) and micro-roughness. Four powerful metrology systems have been researched, developed and used to provide measurement data covering the required low-to-mid-to-high spatial frequency information about the 4.2 m optical surface. Customized interferometry using computer generated hologram (CGH) and the Software Configurable Optical Testing System (SCOTS) deflectometry system have been used to measure the overall surface figure. The newly developed Slope Measuring Portable Optical Test System (SPOTS) covers the mid-spatial frequency metrology. In order to measure the local micro-roughness, Micro Finish Topographer (MFT) using temporal phase shifting interferometry has been used on various local spots on the DKIST mirror surface. All measurements are converted to PSD plots and combined in spatial frequency domain. The measured PSD covering the wide surface error spectrum without missing bands shows an excellent super-polished surface quality of the large aspheric mirror, which is going to enable a new level of solar science.

9912-15, Session 3

Freeform and advanced optics for ELT instrumentation

Roland Geyl, REOSC (France)

The E-ELT will be equiped with advanced instrumentation and Reosc wish you highlight recent technology developments that shall allow the design and realization of more performant optical instrumentation than ever.

Freeform surfaces : Recent development in freeform optics for space application will be presented with their potential application to spectrographic instrumentation.

R-SiC polishing layer: This new SiC substrate cladding and polishing technology will be presented. It shall allow a much more easy and less expensive use of SiC material in advanced instrumentation, including cryogenic one.

Extreme aspheric: A demonstration of extreme aspheric optic has recently been made with a 500 mm aperture OAP with 90° deviation and F/2.5 output NA polished to laser quality. This example shall push more far away the technological limitations the instrument designers take into account in their design work.

9912-16, Session 3

Fabrication of an ultra-lightweight Zerodur mirror

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A 1.2-m mirror ultra-lightweight mirror was manufactured by Schott from Zerodur glassy ceramic. This mirror was machined from the back to achieve 85% lightweighting with respect to a solid mirror. A pressure-balanced technique is being used for grinding and polishing the optical surface that limits the print-through effect of the thin facesheet. This paper presents the design of the mirror and its mount, as well as the manufacturing steps to generate the blank and finish the optical surface.

9912-17, Session 3

TIF and material removal characteristics of SiC mirror materials using OVT

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TIF (Tool Influence Function) has been a representative parameter to quantify the material removal characteristics for optical surfaces. We generated a pseudo Gaussian-like TIF on Silicon Carbide (SiC) mirrors with different machine input parameters using Orthogonal Velocity Tool (OVT). The OVT was a polishing tool implemented with orthogonal velocity fields and SiC materials fabricated by diverse production methods. In addition, material removal coefficient of Preston Equation can be calculated by the experimental contact area and relevant translation. Both the TIF and the coefficient could be used as a parameter to characterize the optical surface for various SiC materials. In this paper, we present technical details of experiments and results.

9912-18, Session 4

ZERODUR thermo-mechanical modelling and advanced dilatometry for the ELT generation *(Invited Paper)*

Ralf Jedamzik, Clemens Kunisch, Thomas Westerhoff, SCHOTT AG (Germany)

Large amounts of low thermal expansion material are required for the upcoming ELT projects. The main mirror is designed using several hundreds of hexagonal 1.4 m sized mirror blanks. The M2 and M3 are monolithic 4 m class mirror blanks. The mirror blank material needs to fulfill tight requirements regarding the CTE specification and homogeneity. Additionally the mirror blanks need to be dimensionally stable for more than 30 years. In particular, stress effects due to the changes in the environment shall not entail shape variation of more than 0.5 ?m PV within 30 years. In 2010 SCHOTT developed a physical model to describe the thermal and mechanical long time behavior of ZERODUR®. The model enables simulation of the long time behavior of ZERODUR® mirror blanks under realistic mechanical and thermal constraints. This presentation shows FEM simulation results on the long time behavior of the ELT M1, M2 and M3 mirror blanks under different loading conditions. Additionally the model results will be compared to an already 15 years lasting long time measurement of a ZERODUR® sample at the German federal physical standardization institute (PTB). In recent years SCHOTT pushed the dilatometer measurement technology to its limit. With the new Advanced Dilatometer CTE measurement accuracies of +- 3 ppb/K and reproducibility's of better 1 ppb/K have been achieved. The new Advanced Dilatometer exhibits excellent long time stability. New CTE measurements based on the advanced dilatometer confirm the excellent CTE homogeneity in the single digit ppb/K level on short and long scales.

9912-19, Session 4

Fused silica challenges in sensitive space applications

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Space bound as well as earthbound spectroscopy of extra-terrestrial objects finds its challenge in light sources with low intensities. High transmission for every optical element along the light path requires optical materials with outstanding performance to enable the measurement of even a one-photon event. Using the Lunar Laser Ranging Project and the VIRGO Gravitational Wave Detector as examples, the influence of the optical properties of fused silica will be described. The Visible and Infrared Surveillance Telescope for Astronomy (VISTA) points out the material behaviour in the NIR regime, where the chemical composition of optical materials changes the performance. Special fibres are often used in combination with optical elements as light guides to the spectroscopic application. In an extended spectral range between 350 and 2,200 nm Heraeus developed STU fibre preforms dedicated for broad band spectroscopy in astronomy. STU fibres in the broad spectral range as well as SSU fibres for UV transmission (180 – 400 nm) show also high gamma radiation resistance which allows space applications.

9912-20, Session 4

Manufacturing zero thermal expansion cordierite ceramics aspheric mirrors with Magneto-Rheological Finishing (MRF)

Jun Sugawara, Krosaki Harima Corp. (Japan); Chris Maloney, QED Technologies, Inc. (United States)

Advanced Cordierite (2MgO-2Al2O3-5SiO2) ceramics have both an ultra-low CTE (coefficient of thermal expansion) of 0.03 ppm/K or less at room temperature and a pore-less microstructure. In addition, advanced cordierite ceramics have strong mechanical properties and high, long term dimensional stability for enduring heat cycles. These properties make it a perfect candidate to be used for lightweight satellite mirrors for geostationary earth observation with high spatial resolution and for mirrors for ground-based astronomical metrology; more specifically, an infrared spectroscope. The properties of advanced cordierite ceramics are not only being utilized for structural components of steppers for LSI lithography but also as primary standards and laser mirrors in the field of precision metrology. The advanced cordierite ceramics laser reflecting flat-mirrors with light-weight boxed structures made by diffusion bonding technology were reported in a previous paper. The paper shows that the pore-less microstructure achieved by the polishing realizes a smooth surface with averaged-roughness (Ra) of around 0.3 nm and a flatness of less than lambda/10. To expand upon this previous work to the field of astronomy, aspheric shapes are required for mirrors.

To realize the high precision aspheric shapes made of advanced cordierite ceramics, the deterministic aspherization and figure correction capabilities of Magneto-Rheological Finishing (MRF) will be tested. The first phase of the testing is a material compatibility study. Two types of the advance cordierite ceramics have been prepared and then finished by MRF. The first cordierite (N117B) is a polycrystalline ceramics consisting of one crystal phase. The second (CD107) is a polycrystalline ceramics consisting of main and sub crystal phases. For the MRF material compatibility, a Q-flex 100 machine (QED Technologies) and 4 types of fluid have been used. CD107 with D20 fluid (diamond abrasive fluid) is the best performing combination of MRF fluid and material, resulting in the lowest surface roughness of RMS ~0.8 nm after MRF.

The second phase of testing will start with a conventionally polished 100 mm diameter sphere made of CD107 and MRF will be used to polish in a hyperbolic shape to the mirror as well as provide high precision figure correction. Based on these results, we conclude that MRF polishing has a strong possibility to be a very promising technique for producing the advanced cordierite aspheric mirrors.

9912-21, Session 4

Silicon carbide main structure for EUCLID NISP instrument in final development

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The Euclid project is part of ESA's Cosmic Vision program with its launch planned for 2020. The Euclid mission main scientific goal is to understand the accelerated expansion of the Universe by mapping the geometry of the dark Universe. The mission will investigate the distance-redshift relationship and the evolution of cosmic structures by measuring shapes and redshifts of galaxies and clusters of galaxies out to redshifts ~2, or equivalently to a look-back time of 10 billion years. The NISP (Near Infrared Spectro-Photometer) is one of the two Euclid instruments operating in the near-IR spectral region (0.9-2?m) as a photometer and spectrometer. The development of the instrument is currently in phase C.

LAM has in charge the development of the main structure of the NISP instrument. This mechanical assembly will support six main optomechanical modules and work at 132 K. These modules require very high positioning accuracy and a very high stability in operation (a few tens of microns) to achieve the required optical performances and so the scientific goals.

In this context, a structure made of Silicon Carbide (SiC) supporting by an invar hexapod, ensuring a very high stability with a very good mass stiffness ratio, is developed at LAM.

This article describes the challenging design of this optomechanical concept taken into account the complexity of the interfaces and the very high accuracy of the manufacturing tolerances. Static, dynamic and thermomechanical associated analyses have been performed. These studies, allowing to demonstrate the thermomechanical strength of the structure and so validate the design choice, are documented and detailed. Finally, future vibrations tests planned at Centre Spatial de Liège (CSL) on the hardware, currently realized by sub-contractor, will be presented.

9912-22, Session 4

A study on a fabrication process for CFRP mirror

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Most favorable materials for telescope mirrors are Zerodur, Clearceram-z, Astrosital, and ULE, as they have low thermal expansion values and easy production. However, they need careful manipulations as they are brittle. Especially when they are applied to space telescopes, deeper attentions should be paid during the harsh launch environments.

CFRP material has a great potential for a next generation mirror especially for space telescopes. The stiff and light-weight mirror will reduce the risk of launches and the production costs eventually. Efforts have been poured to produce CFRP mirrors worldwide, and the key success factor looks fabrication method and process. In this paper, a fabrication process is presented. When the CFRP mirror becomes available, it would benefit mobile equipment as well as space telescopes.

9912-23, Session 5

Fabrication and testing of the 4.2m off-axis primary mirror of DKIST

Chang Jin Oh, Andrew E. Lowman, Greg A. Smith, Run Huang, Tianquan Su, Peng Su, Daewook Kim, Chunyu Zhao, James H. Burge, College of Optical Sciences, The Univ. of Arizona (United States)

Daniel K. Inouye Solar Telescope (formerly known as Advanced Technology Solar Telescope) is the largest optical solar telescope ever built to provide greatly improved image, spatial and spectral resolution and to collect sufficient light flux of Sun. To meet the requirements of the telescope the design adopted a 4m aperture off-axis parabolic primary mirror with challenging specifications of the surface quality including the surface figure, irregularity and BRDF. The mirror has been completed at the College of Optical Sciences in the University of Arizona and it meets every aspect of requirement with margin. In fact this mirror may be the smoothest large mirror ever made.

The fabrication and metrology support has been developed using 118 hydraulic actuators with force calibration for the 75mm thick and 4m aperture membrane mirror and the support demonstrated the extremely accurate and stable performance. During the grinding stage the fabrication process has been guided by a large spherometer and Laser Tracker. During the fine grinding stage IR deflectometry played a critical role revealing the entire ground surface in sub micron level. for the final polishing two redundant metrology systems have been applied. one is Highly accurately calibrated Visible Deflectometry and the other is an Interferometry using a CGH. To achieve efficient progress in fabrication and extremely fine surface finish, computer controlled fabrication has been applied.

The completed mirror presents less than 20nm RMS figure in the full clear aperture, less than 5nm RMS irregularity over 100mm-1mm spatial scale, 1Angstrom micro surface roughness and particularly BRDF is better than 0.6steradian, which is only fraction of the specification.

This paper presents the detail fabrication process and metrology applied to the mirror from the grinding to finish, that include extremely stable hydraulic support, IR and Visible deflectometry, Interferometry and Computer Controlled fabrication process developed at the University of Arizona.

9912-24, Session 5

New and improved technology for manufacture of GMT primary mirror segments

Daewook Kim, The Univ. of Arizona (United States); James H. Burge, College of Optical Sciences, The Univ. of Arizona (United States); Jonathan M. Davis, Hubert M. Martin, Michael T. Tuell, Logan Graves, Steve C. West, The Univ. of Arizona (United States)

The Giant Magellan Telescope (GMT) primary mirror consists of seven 8.4 m light-weighted honeycomb mirrors that are being manufactured at the Richard F. Caris Mirror Lab (RFCML), University of Arizona. Since the first off-axis segment was successfully completed in 2012, the second and third off-axis segments have been cast and the only on-axis center segment is in the process of spin casting. In order to manufacture the largest and most aspheric astronomical mirrors in human history various high precision fabrication and testing technologies have been developed, researched and implemented at the RFCML. It includes a 28 m tall test tower with Computer Generated Hologram (CGH) interferometer, laser tracker, pentaprism scanning system and direct slope measuring deflectometry system. The 8.4 m (in mirror diameter) capacity fabrication facilities are also fully equipped with large optical generator (LOG), large polishing machine (LPM), stressed lap, rigid conformal lap (RC lap) and their process simulation/optimization intelligence called MATRIX. While the core capability and key manufacturing technologies have been well demonstrated by completing the first GMT off-axis segment, there have been significant hardware (H/W) and software (S/W) level improvements in order to maximize GMT primary mirror manufacturing efficiency. Major fabrication system upgrades include LOG H/W and S/W improvement allowing 8.4 m in diameter freeform surface generating, Micro Diamond Finishing (MDF) process, fast fine grinding and polishing process leveraging Trizact diamond pads, MATRIX with multiple tool optimization feature, and stressed lap with orbiting stroke motion. The metrology systems have been also enhanced in many aspects. The interferometric principal test has been thoroughly reviewed and updated using up-to-date technologies such as higher spatial resolution interferometers. For ground surface measurements (during grinding phase) laser tracker system with a new calibration tools and infrared deflectometry system have been developed and tested. The data processing S/W for various GMT deflectometry systems has been continuously enhanced by applying more robust calculations and systematic data handling methods. The new and improved manufacturing technology plays a key role to realize GMT, the next generation extremely large telescope, with high efficiency and confidence.

9912-25, Session 5

Polishing and testing of the 3.4 m diameter f/1.5 primary mirror of the INO telescope

Tapio K. Korhonen, Perttu Keinänen, Mikko Pasanen, Opteon Oy (Finland); Ahmad Darudi, Iranian National Observatory (Iran, Islamic Republic of); Jonathan Maxwell, Optical Consultant (United Kingdom)

Polishing and testing methods used in manufacture of the 3.4 m INO primary mirror are described and the test results of the finished mirror are presented.

Mirror lapping and polishing was performed using several rectangular non-rotating tools arranged in a linear array across the mirror radius. Each tool is equipped with two computer controlled force actuators for regulating the surface pressure and removal efficiency during the lapping and polishing operations. The same tool system was used from the beginning of the lapping phase to the end of the final polishing.

During lapping phase the mirror surface errors were measured with a profilometer to accuracy of about 1 micron RMS. During polishing mirror measurements were made with pentaprism test to verify the correct conic constant of the mirror. The principal optical test method was the interferometric Hartmann test with the aid of a two component null lens in the mirror center of curvature. In the test arrangement the miniature Hartmann mask is behind the second element of the null lens and in the final tests it has about 7500 holes with equal spacing in a rectangular grid. The sampling spacing on the mirror surface is about 33 mm. In a complete test procedure the mirror is measured in 12 different rotational positions with increases the number of the sampling points to about 22500. The rotation also eliminates effects originating from possible alignment errors of the null lens. In each rotational position a large number of measurement images are averaged to eliminate the effects from air turbulence and vibrations.

The mirror was finished to extremely good surface accuracy. After subtraction of some low frequency aberrations of very small amplitude the residual high frequency mirror surface error is 4 nm RMS. Also the smoothness of the surface is very good and uniform. The micro-roughness within measured areas of about 1 mm diameter is 0.6 nm RMS and it is uniform within +- 0.1 nm.

9912-26, Session 5

Modern technologies of fabrication and testing of large convex secondary mirror

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Modern large telescopes such as TAO, LSST, TMT and EELT require 0.9m-4m monolithic convex secondary mirrors. The fabrication and testing of these large convex secondary mirrors of astronomical telescopes is getting challenging as the aperture of the mirror is getting bigger. The biggest challenge is to measure the large aspheric convex surfaces to a few nanometers, while maintaining the testing and polishing cycle to be efficient. For the last a couple of decades there has been a huge advancement in metrology and fabrication of large aspheric secondary mirrors. College of Optical Sciences in the University Arizona developed a full fabrication and metrology process with extremely high accuracy and efficiency for manufacturing the large convex secondary mirrors.

This paper presents modern metrology and fabrication process including Swing-Arm Optical Profilometer which is comparable to Interferometry, a Sub-aperture stitching interferometry scalable to a several meters and a Computer Controlled Fabrication Process which produces extremely fine surface figure and finish. Also this most recent development has been applied to the fabrication of the 0.9m secondary mirror of TAO telescope and verified.

9912-27, Session 5

Advanced mirror technology development (AMTD) project: overview and year four accomplishments

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The Advance Mirror Technology Development (AMTD) project is a multi-year effort initiated in FY12 to mature technologies required to enable 4 to 8 meter (or larger) UVOIR space telescope primary mirror assemblies for both general astrophysics and ultra-high contrast observations of exoplanets. AMTD Phase 1 completed all of its goals and accomplished all of its milestones. AMTD Phase 2 started in 2014. Key accomplishments include deriving primary mirror engineering specifications from science requirements; developing integrated modeling tools and using those tools to perform parametric design trades; and demonstrating new mirror technologies via sub-scale fabrication and test. AMTD-1 demonstrated the stacked core technique by making a 43-cm diameter 400 mm thick 'biscuit-cut' of a 4-m class mirror. AMTD-2 is demonstrating lateral scalability of the stacked core method by making a 1.5 meter 1/3rd scale model of a 4-m class mirror.

9912-28, Session 5

Large Synoptic Survey Telescope camera design and construction

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The Large Synoptic Survey Telescope (LSST) Camera is being constructed for the large-aperture, wide-field, optical imaging facility designed to address some of the most pressing questions about the structure and evolution of the universe and the objects in it. The LSST Camera with three refractive lenses and a 9.6 square degree field-of-view will take pairs of 15-second exposures of the southern hemisphere. The Camera has a 3.2-gigapixel flat focal plane array with 4K x 4K CCD sensors. The sensors are deep-depleted, back-illuminated devices with a highly segmented architecture that enables the entire array to be read out within 2 seconds. Sensors are mounted on a silicon carbide grid inside a vacuum cryostat, and will operate at -100ºC. There are three refractive lenses, L3 is the entrance window to the cryostat and L1 and L2 are mounted in an optics structure at the front of the camera body, which also contains a mechanical shutter and a carousel assembly that holds all the large optical filters. The LSST Camera received approval to start fabrication of the sensors in 2014 and approval all other components in 2015. A summary of the design and construction progress will be presented, as well as the technical challenges.

9912-29, Session 5

Thin glass shells for AO: from plano to off-axis aspheric

Eric Ruch, Emmanuelle Harel, Roland Geyl, REOSC (France)

Reosc is working on thin glass shells for many years and was recently selected by ESO for the E-ELT M4 mirror thin glass shells up to 2.5-m diameter. Previously Reosc also produced the aspheric thin shell for the VLT-M2 AO Facility. Based on this experience we will discuss how off axis thin glass shells can be made for the nex generation AO systems like the GMT one.

9912-30, Session 5

Status of mirror segment production for the Giant Magellan Telescope

Hubert M. Martin, The Univ. of Arizona (United States); James H. Burge, College of Optical Sciences, The Univ. of Arizona (United States); Jonathan M. Davis, The Univ. of Arizona (United States); Daewook Kim, College of Optical Sciences, The Univ. of Arizona (United States); Jeffrey S. Kingsley, Kevin Law, The Univ. of Arizona (United States); Adrian R. Loeff, College of Optical Sciences, The Univ. of Arizona (United States); Randy D. Lutz, Catherine D. Merrill, Peter A. Strittmatter, Michael T. Tuell, Stuart Weinberger, Steve C. West, The Univ. of Arizona (United States)

The Richard F. Caris Mirror Lab at the University of Arizona is responsible for production of the 8.4 m segments for the primary mirror of the Giant Magellan Telescope. Since our last report in 2014, the most significant progress is the successful casting of Segment 4, the center segment. We are currently building the mold for casting Segment 5, the next off-axis segment, in June 2017. On the polishing side, we completed the combined 8.4 m primary and 5.1 m tertiary mirrors for the Large Synoptic Survey Telescope and made progress on a 6.5 m primary mirror; both projects are prior commitments that precede GMT Segments 2-8 in the Mirror Lab queue.

Prior to generating Segments 2 and 3, we carried out a major upgrade of our 8.4 m Large Optical Generator (LOG). The upgrade includes replacement of worn or obsolete mechanics and electronics, and a

completely new set of software with features to improve accuracy, safety, reliability and ease of use. An automated calibration procedure uses a laser tracker to measure and compensate for tool position errors over a 5 m horizontal x 1 m vertical envelope. The generated surface is measured in situ with a laser tracker, allowing rapid turnaround without disturbing the alignment of the mirror on the turntable. An occasional surface measurement using an enhanced laser tracker system in the optical test tower serves to calibrate the in situ measurements and provide measurement accuracy of about 5 ?m. The tool path is adjusted to correct for the measured surface error using a LOG-specific module in SAGUARO, a MATLAB-based data processing platform that provides standard manipulation and analysis of optical data from multiple sources.

We are currently designing a similar upgrade of our 8.4 m polishing machine. The first component of the upgrade is an orbital capability for the primary polishing tool, a 1.2 m stressed lap. With GMT Segment 1 and the LSST mirrors, we were able to achieve very predictable removal and good figure convergence using an orbital polishing system with control of dwell as a function of position. The original system was designed for small compliant tools, and was very effective for mid-scale figure errors. Combining this system with a large, stiff stressed lap should lead to more efficient correction of large-scale errors and better passive smoothing of small-scale errors.

A set of optical tests measures the mirror figure on scales from 8.4 m down to about 1 cm. The overlapping capabilities of the tests provide redundant measurements of critical parameters, in particular the radius of curvature and low-order aberrations. We added and modified several components of the tests during the manufacture of Segment 1, and we have continued to improve the systems in preparation for Segments 2-8. We will have a new interferometer with improved spatial resolution, and improved alignment references for the large, asymmetric null corrector. We have also implemented and refined two test systems based on deflectometry that provide better spatial resolution than the interferometer and can guide figuring on all necessary scales.

9912-31, Session 5

LSST camera lens manufacture

Mark A. Smith, Arizona Optical Systems, LLC (United States); Andrew Fox, Corning Incorporated (United States); William Raggio, Rayotek Scientific, Inc. (United States); Justin P. Hoover, Benjamin Lewis, James H. Burge, Martin J. Valente, Arizona Optical Systems, LLC (United States)

The Large Synoptic Survey Telescope (LSST) is a three-mirror 8.4-m telescope that achieves 3.5° field of view with 0.2 arcsecond sampling. Field lenses made from Corning fused silica are used to provide high quality images over the 64-cm diameter 3.2 gigapixal focal plane. This paper discussed the fabrication of the large field corrector lenses. The largest, L1, is 1.57 meters in diameter and only 32 mm thick at the edge. The second lens (L2) is 1.17 meters in diameter, 30 mm thick, and incorporates an aspheric surface. The manufacture and test of the fused silica glass blanks is described. An overview of subsequent processing including diamond generating, grinding, and polishing is provided with special emphasis on solutions to the unique challenges presented by these lenses.

9912-32, Session 5

Manufacture and final tests of the LSST monolithic primary/tertiary mirror

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The LSST M1/M3 combines an 8.4 m primary mirror and a 5.1 m secondary mirror on one glass substrate. The combined mirror was completed in October 2014. Interferometric measurements show that both mirrors have surface accuracy better than 20 nm rms over their clear apertures, in near-simultaneous tests, and that both mirrors meet their stringent structure function specifications. The optical axes of the two mirrors coincide to better than 0.5 mm at the surface of M3 and are parallel to better than 4 ?rad. The parameters of the optical prescriptions and all mechanical dimensions have been measured to be within their specified tolerances.

The LSST M1/M3 mirror was spin-cast in March 2008. The rear surface was ground and polished over the period January - September 2009, followed by bonding of loadspreaders, hardpoint wedges and thermocouples from September to December 2009. The front surfaces were generated from January to October 2010, followed by successful repair of a region that was damaged at the end of the generating process. Loose-abrasive grinding was carried out on M1 from April to August 2011 and on M3 from September 2011 to March 2012. Polishing of both mirrors covered the period April 2012 - October 2014. M1 was finished first, in April 2014, and M3 was finished in October 2014. Acceptance tests were conducted from October 2014 to February 2015.

The mirror figures are obtained with a simulated active optics correction that uses the 156 support actuators to bend the glass substrate. Before the active optics correction is applied, corrections are made for small errors in support forces and small temperature gradients measured in the substrate. The active optics correction affects both mirror surfaces simultaneously. We used near-simultaneous tests of both surfaces, along with the simulated correction, to show that both mirrors have excellent figures and meet their specifications with a single set of correction forces. The magnitude of the forces is less than half the allowed amount.

The interferometers do not resolve some small surface features with high slope errors. We used a new instrument based on deflectometry to measure many of these features with sub-millimeter spatial resolution over 12.5 cm apertures. Working with LSST staff, we created synthetic models of both mirrors by combining the interferometric maps and the small high-resolution maps, and used these to calculate the impact of the small features on images. The impact was found to be acceptably small.

In this paper we summarize the fabrication process and tests, document the quality of the mirror, and present the results of the analysis of small-scale features.

9912-33, Session 6

Large aperture modular freeform VIS telescope with smart alignment approach

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Metal mirrors are key components for small and medium sized instruments used within space or ground based astronomical applications. Optical systems based on metallic substrates offer a high degree of integration, which belongs to a direct monolithic fabrication of datum and reference

planes, metrology fiducials, or decoupling mounting interfaces at the mirror substrate itself. Using servo assisted diamond machining techniques, optical surfaces and mechanical references are manufactured in the same machining operation, which results in an exact knowledge between the optical and mechanical coordinate systems. By applying ultra-precision diamond machining techniques to the mechanical telescope structure, all interfaces can be generated highly accurate in shape and position.

A strict application of this reference based machining and metrology approach enables a simplified assembly of the whole optical system. Individual parts of the telescope are snapped together at their ultra-precisely machined interfaces, while the integration is reduced to a few relative alignment steps. Further improvements are achieved, if the optical design allows for special fabrication approaches that make use of a modular arrangement of single surfaces on common mechanical carriers. Two mirrors can be simultaneously machined in a common toolpath to fix the relative position between the surfaces with uncertainties as low as the machine precision. The combined fabrication is coupled to a further reduction of the open degrees of freedom that have to be considered in the final telescope integration step.

Snap-together approaches were traditionally developed for infrared (IR) applications having relative loose tolerances on figure and position, where the required precision is achieved by diamond machining only. Using local figure correction and polishing techniques such as Magnetorheological Finishing (MRF) and computer controlled polishing (CCP), single surface deviations and remaining position errors can be compensated. The improvements allow for a transfer of the integration approach to applications in the near infrared (NIR) and visual (VIS) spectral range.

The article presents the development, fabrication, and testing of a large aperture, anamorphic imaging four mirror telescope exhibiting a smart alignment approach. Four biconic aspheres are used to transform an incoming 200 x 50 mm? rectangular field of view onto a 90 x 90 mm? square image plane. Optical and mechanical designs intend a simplified system integration by combining each two freeform surfaces on a common mechanical substrate. Using a combination of fast tool servo diamond machining and subsequent MRF figure correction, mirror modules having single surface deviations < 150 nm p.-v. and relative position errors < 1 μm are manufactured. Fabrication and metrology approaches proposed always relate to well defined fiducials that are machined in a combined diamond turning – diamond milling step. Local MRF polishing helps to reduce the final microroughness of the mirror to less than 0.5 nm rms.

System assembly is finally simplified to a snap-together mounting of both mirror modules into the overall telescope structure. The performance is measured over the field of view with the help of a parallel kinematic setup and results are reported.

9912-34, Session 6

Effects of thermal inhomogeneity on 4m class mirror substrates

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The new ground based telescope generation is moving to a next stage of performance and resolution. Mirror substrate material properties tolerance and homogeneity are getting into focus. The coefficient of thermal expansion (CTE) homogeneity is even more important than the absolute CTE. The error in shape of a mirror, even one of ZERODUR®, is affected by changes in temperature, and by gradients in temperature. Front to back gradients will change the radius of curvature R that in turn will change the focus. Some systems rely on passive athermalization and do not have means to focus. Similarly changes in soak temperature will result in surface changes to the extent there is a non-zero coefficient of thermal expansion. When there are inhomogeneities in CTE, the mirror will react accordingly. Results of numerical experiments are presented discussing the impact of CTE inhomogeneites on the optical performance of 4 m class mirror substrates. Latest improvements in 4 m class ZERODUR® CTE homogeneity and the thermal expansion metrology are presented as well.

9912-35, Session 6

Unmanned aerial vehicles in astronomy

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Unmanned Aerial Vehicles (UAVs) are used in a wide range of activities both for civilian and military purposes, for scientific and commercial scopes. Involved fields of interest are getting broader as technological developments make UAVs affordable and reliable tools to position sensors in locations otherwise difficult or unsafe to access or expensive for other options. The ability of UAVs to pinpoint positions with increasing precision and automation goes along with the evolution of laser ranging sensors in term of compactness and lightness, allowing them to be employed in a number of metrological measurements for natural or artificial structures otherwise difficult to properly sense.

Considering all these benefits, the use of UAVs in astronomy is a step to be considered for valuable contributions in making some procedure easier and cheaper. Although applications of UAVs for strictly astrophysical objectives have not planned yet, we consider a wide spectrum of possibilities for them to be used as facilities for Ground Based Telescopes. Here we describe a non-exhaustive list of possible applications that we at least try to briefly discuss, emphasizing the applications in the field of alignment and maintenance of the telescopes and seeing measurements.

Nowadays, a dozen of 8 to 10 m diameter class telescopes are employed for astronomical purposes and the generation of Extremely Large Telescopes (diameter of 24 to 39 m) is in advanced phase of construction. Alignment of these telescopes, in order to achieve nominal performances, is an important asset, especially taking into account the relatively high operation costs of such devices. Primary mirrors can be tested in daylight condition placing a calibration device in their centre of curvature. Moreover, every time an intermediate real focus is identified, all the optical train following such a point can be easily adjusted with a simple calibration device to be inserted in the proper position. Since for 30 m telescopes with a very fast (F/1) optical primary, such a device should be located about 60 m away from the primary mirror to align it and for popular Cassegrain telescopes the autocollimation point is even more distant to align the secondary, it is clear that the use of a UAV to reach those locations would set aside the need for expensive and inconvenient static structures, employed only in few cases (McDonald telescope in Texas is a notable case).

Other examples of daylight activities of telescope maintenance, potentially performed by an adequately equipped UAV, are the measurement of the cophasing of adjacent surfaces, scattering and reflectivity of tiles of segmented mirrors. UAVs can be employed overnight in monitoring environmental parameters, like Cn2 and Ct2 that would be measured dynamically for an arbitrary thick ground layer and in exploring fine details in the dome seeing evolution.

In this work we discuss the prospects of use of UAVs for these mentioned activities, relating them to a small number of parameters, and tracing which could be the schemes, requirements, and benefits for employing them in the telescope alignment, both at the stages of erection and maintenance.

9912-36, Session 6

Coordinate metrology of a primary surface composite panel from the Large Millimeter Telescope

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The Large Millimeter Telescope (LMT) Alfonso Serrano is a fully steerable single-dish radio telescope presently operating with a 32.5 m parabolic primary reflector, soon to be extended to 50 m. The primary surface is composed of 180 segments arranged in five concentric rings. Each segment is formed by a set of 8 precision composite Nickel reflective panels. Five height-adjustable support points per panel allow surface adjustment to the local design parabola prior to segment installation. Since 2011 the project has used commercial laser trackers to measure the surface shape of the panels, not only for initial adjustment, but also for periodic checks after installation in the antenna. More recently, photogrammetry has been used to provide a sanity check of the tracker data.

The LMT project has invested much effort in developing and verifying surface fitting algorithms, used to transform data point clouds from the measuring instruments into RMS surface error. Conversely, relatively little effort has been spent on attempting to verify the data collection process itself, relying simply on periodic equipment calibration and occasional field checks with linear scale bars. Verification of the measurement process is important for two reasons; firstly, because a poor understanding of equipment–related measurement uncertainty may lead to unreliable results, and secondly because the LMT project routinely uses its metrology equipment at the limits of stated accuracy or beyond the manufacturer's environmental specifications.

Recently the LMT team has started a collaboration project with CENAM, the National Metrology Institute (NMI) of Mexico, to characterize the measurements performed on the curvature of the telescope primary panels, validate these measurement results and establish the measurement uncertainty. For this purpose, a panel was sent to CENAM to be measured horizontally on a high accuracy Coordinate Measuring Machine (CMM) with well-controlled temperature conditions. The panel was also measured using LMT and CENAM laser trackers, and LMT photogrammetry equipment. All measurements were performed by LMT and CENAM personnel, within the controlled laboratory environment at CENAM. This panel will be used hereafter by the LMT project as a reference artifact to make regular checks on our portable coordinate measuring systems and validate subsequent measurements at INAOE and on-site.

In this paper we present some results of the surface panel metrology exercise with an emphasis on the identification and estimation of measurement uncertainties that have relevance to the equipment and procedures used routinely by the LMT project as part of the surface qualification process. We also describe the steps taken to use the sample panel as a calibrated work-piece as described by ISO-15530-3. The creation of a calibrated work-piece is an experimental process that will allow the LMT metrology group to simplify the evaluation of measurement uncertainty when using coordinate metrology techniques such as a laser tracker and photogrammetry.

9912-37, Session 6

Error analysis of back focal length measurement technique for long focus larges-scaled lenses

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The technique for positive long focus lenses allows to perform back focal length and transmitted wavefront measurements. Based on high-precision interferometric alignment and laser distance meter system (laser tracker) the technique allows measuring the back focal length with high precision. Testing of transmitted wavefront is done by means of an autocollimation optical system based on dynamic phase-shifting interferometer. The major contribution to the technique precision is the instrumental errors. The main instrumental error sources and their correlation with a measurement process were found. The main components of instrumental error are optical system alignment error, laser tracker measurement error, error of manufacturing additional accessories. Statistical modeling showed that this technique has a relatively measured precision value of less than 0.003%.

9912-38, Session 7

Evaluation of novel approach to deflectometry for high accuracy optics

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A deflectometrical facility was developed at Italian National Institute for Astrophysics-OAB to characterize free-form optics with shape errors within few microns rms.

Deflectometry is an interesting technique because it allows the fast characterization of free-form optics. The capabilities of deflectometry in measuring medium-high frequencies are well known, but the low frequencies error characterization is more challenging. Our facility design foresees an innovative approach based on the acquisition of multiple direct images to enhance the performance on the challenging low frequencies range.

This contribution presents the error-budget analysis of the measuring method and a study of the configuration tolerances required to allow the use of deflectometry in the realization of optical components suitable for astronomical projects with a requirement of high accuracy for the optics. Test examples are the primary mirrors for the E-ELT and the MAORY mirrors.

9912-39, Session 7

Laboratory and field testing results of the LMT/GTM primary surface actuators

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With the final installation of the two outermost rings of the primary surface of the Large Millimeter Telescope/Gran Telescopio Milimetrico (LMT/GTM), the project is also upgrading the primary surface actuators. There are commercial actuators that can approach the required operational accuracy and stroke, but the combination of the size and load requirements ultimately required a customized design. The new actuators fit within the volume constraints imposed by the tighter interior angles in the outer rings and are designed to support the operational and survival loading conditions even for the largest surface segments. Laboratory testing confirmed that the actuators should meet the precision, repeatability, load, and lifetime requirements.

However, the LMT/GTM is at a particularly difficult site for electromechanical systems. The high altitude has the usual effect of reducing cooling effectiveness for the drives and motors, and the ambient temperature hovers near freezing. Since there is a significant amount of

precipitation during some times of the year, there are frequent freeze/thaw cycles. The constant formation and either sublimation or melting of ice, along with the associated high humidity, has been a challenge for the environmental protection of many devices at the LMT/GTM. Because there are a total of 720 primary surface actuators in the system, it is particularly important that the actuators, their local drive control boxes, and their cable connections be able to meet its specifications even under the site conditions.

To confirm the suitability of the actuators, the LMT/GTM procured an initial set of sixteen actuators for testing at the site. After laboratory testing, the actuators were installed into the outer two rings of the telescope and cycled during the early winter months of the 2015-2016 scientific observing season. Because of the continuing installation activities in these two rings, they are not illuminated by the receivers, so field testing under actual operational conditions could be conducted without affecting the ongoing scientific observations. This paper presents the characterized performance of the actuators before and after testing, as well as a report on their environmental robustness.

9912-41, Session 7

Optical tests of the Si immersed grating demonstrator for METIS

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We present the optical tests of the silicon immersed grating (IG) demonstrator for the Mid-infrared E-ELT Imager and Spectrograph, METIS. IG-s offer several advantages over conventional front-surface gratings. Since diffraction takes place inside the high-index of refraction material, the optical path difference and angular dispersion are increased proportionally. Consequently, a smaller grating area and beam diameter is sufficient to obtain the same spectroscopic resolution, so a significant reduction of spectrometer volume becomes possible. Also, using the available expertise and techniques of the semiconductor industry, IG-s can achieve higher diffraction efficiency and lower stray light levels.

The METIS IG demonstrator is produced on a 150 mm industry standard for wafers. Similarly, standard semiconductor lithography techniques and anisotropic etching in silicon are used to define grating grooves with nanometer accuracy and sub-nanometer roughness. Optical bonding is used then to combine the wafer and silicon prism, followed by thermal fusion to strengthen the wafer-prism bond.

In the current paper we discuss the results of the IG tests that were performed in order to verify the optical requirements of the component. We detail the interferometric tests that were done to measure the wavefront error. A HeNe laser interferometer operated at 633nm was used to measure the entry/exit facet as well as the grating surface itself from air-side in various orders, in different grating orientations. We present the wavefront error budget of the complete IG and show how the wavefront error of various sources were deduced and calculated from the measurements. We present the optical arrangement and the results of the throughput measurements that were done with a modified infrared Fourier Transform Spectrometer (FTS). The measurement gave insight into the diffraction efficiency of the grating knowing the AR coating characteristics of the entrance/exit surface. Throughput was measured over the complete operational wavelength range of the METIS spectrograph, between 2.9?m and 5.3?m. We also show the dedicated mounting arrangement and results of the BRDF (Bidirectional Reflection Distribution Function) measurement that were performed with a Complete Angle Scatter Instrument (CASI) in spectral and spatial direction. Wafer defects observed after optical contacting and bonding (between the prism and wafer) were investigated as well. We present the lessons learnt during the IG demonstrator test campaign and elaborate on the challenges that we encountered, especially during the wavefront error measurements that led us to investigate further and improve the fabrication processes of the grating patterning on the silicon wafer.

9912-42, Session 8

Optical performance analysis and test results of the EUCLID near-infrared ?spectro-photometer

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The Near Infrared Spectrometer and Photometer (NISP) of the EUCLID satellite ?project encompasses high precision large lens mounts of 168 mm diameter that are ?operated at cryogenic temperatures down to 135K. The four lenses of the optical ?system are made of different materials: SUPRASIL 30001, CaF2, and S-FTM16, ?which are mounted in a separate lens mount design using glue connections. Each ?lens assembly has its individual mechanical interface to the structure, the so called ?lens barrel.

Exhaustive structural and thermal investigations ?have determined lens surface ?deformations and lens position ?changes that are introduced by ?various ?environmental loads, such as thermal-, mechanical-, ?interface-, and gravity ?loads, as well as ?mechanical stress of the lenses due to glue shrinkage ?during ?curing. All these impacts change the ?lens optical behaviours under real ?operational ?conditions of ?the optical assembly, which are thoroughly investigated in ?the optical performance assessment activity.?

Especially, great effort has been made for the simulation of interface tolerances. ?Due to the complexity of all mechanical interfaces (baffle, lens mounts, housing, ?telescope structure, etc.) statistical simulation is conducted applying ?Monte Carlo ?method. From the result of the statistical simulation 3 representative cases are ?selected for the optical performance assessment, which have 95% confidence level ?of the lens surface deformation.?

In the context of the evaluation procedure the surface form error of all EUCLID ?lenses as well as the RMS ?WFE at the ?focal plane is assessed, and results are ?compared with the nominal ?performance of the ?system, as well as with ?interferometrically measured results achieved during the interface– and gravity ?release test campaign.?

The performance of the lens holder design in terms of glue shrinkage effects, gravity ?release and interface tolerances is verified by an adapted test facility including an ?interferometer based optical metrology system. Finally, the measured values are ?compared with the analytical results, which show great confidence and hence ?proves validation of the analytical model.?

The paper presents the optical performance analysis results and the measured ?performance of the EUCLID high precision large cryogenic lens mounts. The ?achievements are presented on behalf of the EUCLID consortium.?

9912-43, Session 8

GMTIFS: the adaptive optics beam steering mirror for the GMT integral-field spectrograph

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To achieve the high adaptive optics sky coverage necessary to allow

the GMT Integral-Field Spectrograph (GMTIFS) to access key scientific targets, the on-instrument adaptive-optics wavefront-sensing (OIWFS) system must patrol the full 180 arcsecond diameter guide field passed to the instrument. The OIWFS uses a diffraction limited guide star as the fundamental pointing reference for the instrument. The science target must be held stationary with respect to the guide star. During an observation the offset between the science target and the guide star will change due to sources such as flexure, differential refraction and non-sidereal tracking rates. GMTIFS uses a beam steering mirror to set the initial offset between science target and guide star and also to correct for changes in offset. In order to reduce image motion from beam steering errors to those comparable to the AO system in the most stringent case, the beam steering mirror is set a requirement of less than 1 milliarcsecond RMS. This corresponds to a dynamic range for both actuators and sensors of better than 1/180,000. The GMTIFS beam steering mirror uses piezo walk actuators and a combination of eddy current sensors and interferometric sensors to achieve this dynamic range and control. While the sensors are rated for cryogenic operation, the actuators are not. We report on the results of prototype testing of single actuators, with the sensors, on the bench and in a cryogenic environment. Specific failures of the system are explained and suspected reasons for them. A modified test jig is used to investigate the option of heating the actuator and we report the improved results. In addition to individual component testing, we built and tested a complete beam steering mirror assembly. Testing was conducted with a point source microscope, however controlling environmental conditions to less than 1 micron was challenging. The assembly testing investigated acquisition accuracy and if there was any un-sensed hysteresis in the system. Finally we present the revised beam steering mirror design based on the outcomes and lessons learnt from this prototyping.

9912-44, Session 8

Development of superconducting voice coil motor of a cold chopper for MICHI

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A collaborating group based dominantly in Japan and the USA is investigating the science enabled and instrument design for a Mid-Infrared Camera, High disperser, and Integral field unit, called MICHI for the 30 m TMT. We hope that MICHI could become a strong candidate for the second generation of TMT instruments.

A cold chopper is one of the key elements of MICHI. For ground-based mid-infrared observations, time variations of atmospheric radiation are often many times greater than the radiation from target. Cold chopping is a technique to account for these background variations. 8 m class telescopes have chopped their secondary mirror, but this is impractical for the 30 m class of telescopes due to their much larger secondary mirror. For MICHI, we plan to use a movable mirror in the instrument at 30 K which will enable us to capture two slightly spatially and temporally different images to accurately remove the sky and account for the sky variations.

A cold chopper mirror (35mm diameter) for MICHI/TMT requires a stroke of 2.5 mm, a response time ≤ 10 ms. To prevent a significant power dissipation of the actuator, we require a power dissipation of ≤ 0.1 W.

In order to satisfy these requirements, we focused on Voice Coil Motor (VCM). VCM is a linear and electromagnetic actuator, and can be easily designed and have high responsibility.

Additionally, we use a superconducting wire made from MgB2 which has the highest transition temperature, 39 K, among metal superconductors. Thus VCM using MgB2 wire should work in the superconducting state at 30 K.

The force applied by a VCM is proportional to the applied current and magnetic field. In order to reduce joule heat from wire other than superconducting wire of a VCM, the current of electric circuit which includes a VCM is required to be ≤ 1 Ampere, so the magnetic field strength is a very important element for designing the VCM.

Generally, a neodymium magnet is known as the strongest magnet at room temperatures. But under about 135 K, the magnetic field becomes weak due to the spin reorientation transition. Therefore we use a praseodymium magnet, which produces a stronger magnetic field than the neodymium magnet at 30 K.

The magnet field easily permeates the vacuum. We should design the magnetic circuit to prevent the leakage flux. We select two fundamental designs of VCM and have completed a parameter search to find best design of the actuator for the MICHI cold chopper. We note that even a superconducting VCM produces energy dissipation when there is a variation in the current. This is caused by the magnetic hysteresis. However, it is difficult to estimate the power dissipation of the superconducting wire analytically, thus we use a numerical simulation to estimate the dissipation, and the result showed that the power dissipation is within 0.1 W.

Using these considerations, we made a prototype VCM. We are currently evaluating this VCM and plan to install it in MIMIZUKU, a mid-infrared instrument for the University of Tokyo Atacama Observatory 6.5 m Telescope.

9912-45, Session 8

Characterizing the performance of cryogenic lens mounts for the HARMONI spectrograph

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HARMONI is an optical and near infrared spectrograph that will be the first-light spectrograph on the E-ELT. To minimize the thermal background in the infrared, it will be a cryogenic instrument with an operating temperature of 130K. Cooling down the instrument causes differential thermal contraction, which should be compensated for in the lens mount designs, to allow alignment of the optics at room temperature. The lenses in the current camera design have a diameter of 200mm and need to be centred to an accuracy of around 20?m at the operating temperature.

We have designed 4 different self centring lens mounts and have also developed an alignment procedure based on the idea of avoiding any contact with the lens where possible, to reduce any risk of damage. The position of the lens is measured once with a CMM, with the mount then moved into alignment with it so that it can be used as a mechanical reference for the lens when assembling the camera barrel.

We have performed cryogenic tests on the different lens mount designs and here we present the development of the alignment and bonding procedures as well as the optomechanical performance of mounts.

9912-46, Session 8

Characterization of the actuator of EMIR configurable slit unit

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EMIR (Espectrógrafo Multiobjeto Infra-Rojo) is a wide field multi-object spectrograph for the Nasmyth focus of GTC (Gran Telescopio Canarias). It will operate in the near-infrared (NIR) wavelengths 0.9–2.5μm and it will include several mechanism working at cryogenic conditions.

A key component of EMIR is the CSU (Configurable Slit Unit), which is a cryogenic mechanism used to generate a multi-slit configuration and a long slit on EMIR focal plane when working in spectroscopic mode. The system have 110 sliding bars which can be configured at cryogenic working temperature to create 55 slits with a high position accuracy and repeatability. The movement of the bars is obtained by an actuator which allows to reach a relatively high speed for coarse movement and controllable steps up to 2 microns for fine positioning. This subsystem has been designed and manufactured by Janssen Precision Engineering (JPE) and thoughtfully verified at the IAC (Instituto de Astrofísica de Canarias) facilities.

One of the most critical parts of the CSU are the actuators, which have a design based on a piezo stick-slip effect. In each step there is a first phase in which the bar is dragged in the movement direction (stick) and a second phase in which it should not move (slip), although it really produces a small movement in reverse direction; therefore, the total movement in each step depends on these two effects. The balance between these two phases is strongly affected by other factors such as: the electrical wave used for exciting the piezo, the orientation of movement with respect to gravity and the friction between the bar and the actuator. In this paper we present the results of the tests performed in order to characterize these effects on the two phase movement of the bar.

9912-47, Session 8

A cryogenic “set-and-forget” deformable mirror

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This paper discusses the development, realization and initial characterization of a demonstrator for a cryogenic “set-and-forget” deformable mirror. Many high-end optical instruments on modern large telescopes like METIS (The Mid-Infrared E-ELT Imager and Spectrograph) use either a large number of spherical mirrors or several complex free-form mirrors to manipulate the wavefront to the desired shape. Due to manufacturing and alignment tolerances, each mirror contributes static aberrations to the wavefront. Many of these aberrations are not known in the design phase and can only be measured once the system has been assembled. A “set-and-forget” deformable mirror can be used to compensate for these aberrations, making it especially interesting for systems with complex free-form mirrors or cryogenic systems where access to iterative re-alignment is very difficult.

The mirror with an optical diameter of 200 mm is designed to correct wavefront aberrations of up to 2 μm RMS. The shape of the wavefront is approximated by the first 15 Zernike modes. Analysis of the mirror shows a theoretically possible reduction of the wavefront error from 2 μm to 50 nm RMS (3?). To produce the desired shapes, the mirror surface is supported by 19 identical actuator modules at the back of the mirror. Additional actuators are used to control tip/tilt and piston, providing a larger stroke. This allows for correction of alignment tolerances of the deformable mirror. These additional actuators also introduce redundancy to the system, maintaining optimal performance in case of an actuator malfunction.

The actuator modules have a bidirectional stroke of ±10 μm and sub-nanometer resolution. Elastic flexures are used to eliminate friction and backlash and increase the stability of the mirror shape. To minimize parasitic forces acting on the mirror, the actuator modules are coupled to the mirror using flexible struts. The mirror’s in-plane degrees of freedom are constrained by three folded leaf springs, providing a symmetrical, hysteresis-free connection to the frame.

The actuator modules use commercially available PiezoKnob actuators with a high technology readiness level (TRL). These provide nanometer resolution at cryogenic temperatures combined with high positional stability, and allow for the system to be powered off once the desired shape is obtained. The stiff design provides a high resonance frequency (>200 Hz) to suppress external disturbances.

9912-48, Session 9

Local seeing determination by thermal-CFD analysis to optimize the European Solar Telescope image quality

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The design of telescope facilities which minimize the amount of aerodynamic turbulence flow around them is a key for getting the best possible performance out of a telescope. This is especially true in the case of solar telescopes such as the European Solar Telescope (EST), a large aperture solar telescope (4 meters) that will be located in the Canary Islands. Solar radiation has a critical impact onto the image quality because of the turbulence generated by large temperature gradients at ground level. Therefore, an analysis of the optical distortion due to turbulent effects and the influence of facilities on these parameters is required.

The purpose of this paper is to present the results of thermal and computational fluid dynamics (CFD) analyses of the telescope environment (dome, pier, building, ground, etc.), in order to evaluate the local seeing effect caused. The objective is to keep the temperature of the surfaces of the facility as close as possible to the ambient temperature and minimize the local seeing effect. Two major configurations have been analyzed for the telescope facilities in different environmental conditions, open configuration (without conventional dome) and closed configuration (with conventional dome).

The work flow consists in a thermal analysis followed by CFD analysis. The first stage provides temperature maps for the second, once the model is established (day-night cycles comprising two consecutive days – transient analysis). CFD simulations provides accurate convection models for the analysis (LES turbulence model) which have been used to calculate the refractive index structure constant (Cn2) integrated along the telescope optical beam, at three moments of the day: morning, noon and afternoon.

This contribution starts by reviewing the cases of study analyzed during phase III of the EST project, mainly focused on the study of the “open configuration”. Building orientation, materials, coatings and cooling systems are some of the parameters evaluated. The “closed configuration” analysis is divided in four sections:

- Dome without thermal control
- Dome with thermal control
- Heat rejecter effect inside dome
- Observations out of the sun

Finally, the conclusions of the study are presented together with the advantages and disadvantages of both configurations.

9912-49, Session 9

Initial development of high-accuracy CFRP panel for DATE5 antenna

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DATE5 antenna, which is a 5m telescope for terahertz exploration, will be sited at Dome A, Antarctica. It is necessary to keep high surface accuracy of the primary reflector panels so that high observing efficiency can be achieved. In antenna field, carbon fiber reinforced composite (CFRP) sandwich panels are widely used as these panels are light in weight, high in strength, low in thermal expansion, and cheap in mass fabrication.
In DATE5 project, CFRP panels are important panel candidates. In the design study phase, a CFRP prototype panel of 1-meter size is initially developed for the verification purpose. This paper introduces the material arrangement in the sandwich panel, measured performance of this testing sandwich structure samples, and together with the panel forming process. For deicing in the South Pole region, a special CFRP heating film is embedded in the front skin of sandwich panel. The properties of some types of basic building materials are tested. Base on the results, the deformation of prototype panel with different sandwich structures and skin layers are simulated and several types of sandwich structure samples are tested in the conditions of Antarctic weather, a best structural concept is selected. The panel mold used is a high accuracy one with a surface rms error of 1.4 ?m. Prototype panels are replicated from the mold. Room temperature curing resin is used to reduce the thermal deformation in the resin transfer process. In the curing, vacuum negative pressure technology is also used to increase the volume content of carbon fiber. After the measurement of the three coordinate measure machine (CMM), a prototype CFRP panel of 5.1 ?m rms surface error is developed finally.

9912-50, Session 9

Completely open-foldable domes remaining cool in sunshine

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These open-foldable domes are designed for bad-weather protection and maintenance of instruments for astronomical, meteorological and civil-engineering measurements. It is important that all parts of the opened domes remain cool in sunshine for daytime observations: (i) high-resolution observations of the Sun and other astronomical objects visible during daytime and the first part of the night; (ii) meteorological scintillation measurements in a horizontal path between two towers above ice fields, agriculture fields and nature regions giving information about air-temperature and humidity fluctuations; (iii) precision civil-engineering measurements of ground shape and buildings with theodolites and laser scanners.

The open-foldable domes are designed to withstand extreme weather situations of storm and ice formation, as occur on mountains and in arctic regions. The construction is based on very strong textile membranes highly tensioned between steel bows when the dome is closed. The result is a very light-weight dome despite its extremely high wind stability. Consequently, these domes are also very suitable for light-weight open-construction towers. The domes of the GREGOR telescope and the Dutch Open Telescope are the two existing prototypes. Improvements were developed with all parts light-colored to remain cool in solar light.

New textile parts were developed for the GREGOR dome. The connection parts (eyes) between the textile parts now are made from white-colored PETP, a very strong and UV-stable synthetic, instead of the black-colored standard available PVC eyes used before. In addition, the new specially made eyes have a better geometrical shape giving higher stability. The new eyes are not glued to the textile membranes, but locked in textile pockets attached on the membranes. Consequently, it is easy to replace the eyes when necessary.

The rubber seal tubes on top of the dome were of black-colored chloride rubber CR (neoprene). Reason for use of this black rubber was its strength and UV stability; however, disadvantage was heating in sunshine. Nowadays, light-colored UV-stable rubbers are available. Sheet pieces of several rubber types were tested for their temperature rise in sunshine. Values varied from 21.5 to 45 degree Celsius when exposed longer time to solar light. Clearly the best was an EPDM rubber in natural light color. From this EPDM rubber, new rubber tubes were produced and mounted on the GREGOR and DOT domes. Unfortunately, this rubber was not stiff enough to give good sealing and water leakage occurred. It was found that the addition of the black carbon to the rubber compound is essential to get the EPDM rubber stiff enough to get a reliable closing. The solution was found in a special construction, where inside the light-colored EPDM rubber tube a black-colored stiff EPDM rubber is put. The forces necessary for compression of the rubber tubes were measured in several tests. An inside black tube with a circa 1.5 times larger compression force than the original black tubes was applied. The assembling of the black tubes into the light-colored tubes was successfully applied at the DOT and GREGOR domes.

The presentation will give description, drawings and photos of the constructions applied for the newly developed fastenings of the textile membranes and of the sealing rubber tubes.

9912-51, Session 9

New isostatic mounting concept for a space born Three Mirror Anastigmat (TMA) ?on the Meteosat Third Generation Infrared Sounder Instrument (MTG-IRS)?

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The Meteosat Third Generation (MTG) Programme is being realised through the well-established ?cooperation between EUMETSAT and ESA. It will ensure the future continuity with and enhancement ?of operational meteorological (and climate) data from geostationary orbit as currently provided by the ?Meteosat Second Generation (MSG) system. ?

The industrial prime contractor for the space segment is Thales Alenia Space (France) with a core team ?consortium including OHB-Bremen (Germany) and OHB-Munich (Germany). This contract includes ?the provision of six satellites, four Imaging satellites (MTG-I) and two sounding satellites (MTG-S), ?which will ensure a total operational life of the MTG system in excess of 20 years.?

MTG-S carries the Fourier transform interferometry based Infrared Sounder (IRS), the design of which ?contains a Back Telescope Assembly (BTA) which will relay the interferogram beam into the cold ?optics and then to the focal planes. This BTA is based on a new isostatic mounting concept that has ?been developed, in collaboration between OHB and AMOS, for a space born Three Mirror Anastigmat ??(TMA) light-weighted for the MTG IRS. The TMA with additional folding mirror is based on a light-?weighted all-aluminium design. This developed isostatic mounting concept accommodates the TMA ?onto a CFRP structure (Carbon-Fiber-Reinforced-Polymer). The concept is able to cope with an CTE ?mismatch

of about 20 ?m/m between aluminium and CFRP introducing only very limited stresses into ?the sensitive TMA structure. In ?addition the operational temperature of the TMA is below 0°C, which is ?more than ??20K below the ?integration and alignnment temperature, as well as also 20K between ?temperature of the rest of the ?instrument.? Besides the capability to introduce low stresses into the TMA ?structure, ?the design allows to withstand launch loads of up to 47g. ?

The mounting principle is based on six interface ?element made of titanium, each blocking one degree ?of freedom but providing high flexibility for ?the other degrees of freedom. As three different materials ?are used (aluminium TMA, ?titanium I/F Elements, CFRP structure), one of the main challenge was to ?maintain the optical ?interfaces during the transition to 0°C. A ?very stable Line of Sight (LoS) of a few ?microrads could be achieved. ?

Another important aspect was ?to guarantee the pointing performance in the geostationary orbit of ?MTG with changing thermal conditions for the instrument. In addition the gravity release effect as well ?as the shrinkage of the CFRP structure due to the moisture expansion effect had to be considered by ?the development of the mounting system. The analysis results of the preliminary design confirm that ?these ambitious performance requirement can be met with margin. ?

This paper will provide the design of the BTA isostatic mounting and will summarise the consolidated ?technical baseline reached following a successful PDR. Further it will provide the predicted BTA ?performances, including the way forward to be carried out, and will highlight some of the numerous ?challenges and design solutions required to implement this complex relay telescope.?

The authors acknowledge that this work is supported by an ESA funding through the MTG satellites development.?

9912-52, Session 9

Analytical optimization and test validation of the submicron dimensional stability of the CHEOPS space telescope's CFRP structure

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The CHEOPS mission (CHaracterising ExOPlanet Satellite), an ESA PRODEX founded misson, is the first one dedicated to search for transits by means of ultrahigh precision photometry on bright stars already known to host planets. The optical design is based on a Ritchey-Chretien style telescope to provide a de-focussed image of the target stars.

The telescope's mirrors M1, M2 as well as the focal plane detectors are supported by a thermally controlled CFRP structure suspended on isostatic mounts. The dimensional stability of the structural system supporting the optics is a key requirement as it directly impacts the instrument's accuracy. The M1 and M2 mirrors are supported by a tubular CFRP telescope design which has been optimized by analyses down to carbon fiber layer level with the support of extensive sample test results for model correlation and accurate dimensional stability predictions. This sample characterization test campaign has been conducted on samples with different carbon fibre layup (orientation and stack sequence) to measure accurately the Coefficient of Thermal Expansion (CTE) over a wide temperature range extending from -80°C to +80°C. Using the correlated Finite Element model, the fiber orientation combination that minimized the relative displacement between the M1 and M2 mirrors, including the consideration of the thermo-elastic contributions of the isostatic mounts on the overall stability of this optical system, has been identified and selected for the baseline design of the CHEOPS Structure.

A dedicated Structural and Thermal Model (STM) was manufactured and tested with an ad hoc setup to verify the overall structural stability of the optical train assembly. The relative distance between M1 and M2 was measured under thermal vacuum conditions using laser interferometry techniques. Thermal cycling tests were initially conducted to eliminate and characterize settling effects. Then, the structure stability was measured at three stable operational temperatures: -5, -10 and -15°C. The thermally induced M1-M2 misalignment was measured to be between 0.156 and 0.22 micron/°C in the focus direction. Relative mirror tilt and lateral centre shift were also measured. The obtained focus, tilt and centre shift stability were all compliant with the system level requirements and a CHEOPS Structure was successfully delivered for integration on the spacecraft only 1.5 years after project initiation.

This paper describes the novel technique used by Almatech for the analytical optimization of the Cheops CFRP Optical Train Assembly design based on extensive CFRP layout sample characterizations as well as the sub-micron dimensional stability test results performed under thermal vacuum conditions demonstrating its successful validation.

9912-53, Session 10

Developments in active optics for space instruments: an ESA perspective

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The increasing need for higher image resolution for space applications is driving the entrance aperture of optical systems, requiring the use of large primary mirrors either monolithic or deployable (cf ESA's Future Technology Advisory Panel First cycle report lists large monolithic mirrors as one of the 7 enabling technologies). This trend calls for the study of crucial technologies aimed at improving the imaging performance beyond what is currently achievable by classical optical systems.

Active Optics is a very promising example of such enabling technologies, based on the combination of three key technological components:

1. Corrective element (e.g. deformable mirror),

2. Wave front sensor (in order to characterize the aberrated wave front),

3. Algorithms determining the required correction to be applied, based on the wave front sensing results.

Active optics allows correcting for in-flight effects which impact the optical quality of space instruments. In particular, in the case of large mirrors, extreme lightweighting will need to be applied, leading to increased effects due to e.g. thermo-elastic deformations, radiation effects on optical materials, gravity release, etc. that need to be identified and corrected.

Active optics can also decrease the stringent requirements on the manufacturing quality for large optical components (e.g. compensating residual surface figuring errors), reduce structural and thermal design complexity (e.g. relaxing requirements on structure stability) and reduce the outage period of missions caused e.g. by Sun baffle intrusions or eclipses altering the thermal conditions within the instrument.

As such, active optics constitutes a key building block for the improvement of high-resolution imaging capabilities of future missions (namely for optical systems involving large mirrors, either monolithic or segmented) and constitutes a crucial generic technology able to find applications in all classes of optical instruments.

In terms of technological developments, concepts and demonstrators for corrective components (e.g. deformable mirrors) for space applications have already been initiated at ESA, e.g.:

- GSTP R&D activity "adaptive deformable mirror for space instruments" recently completed by Prof. Dr Wittrock's group at the Muenster University.

- TRP R&D activity "Large Aperture Telescope Technology" performed by Microgate, ADS, CNR-INO, INAF-Florence and CGS.

However, the other essential parts of the complete Active Optics correction chain have so far remained relatively untouched in the context of European space applications, namely: the technology performing the sensing of the aberrated wave front, and the strategy to pilot the corrective elements based on the wave front sensing results.

Furthermore, novel concepts for deformable components need to be explored further in order to anticipate the next generation of active optics specifically tailored for the compensation of large optics (e.g. deformable primary, multiple corrective elements, etc.).

This has led to the launch of a new TRP R&D activity "Active Optics Correction Chain for large monolithic mirrors", which is run in the frame of 2 parallel contracts (TNO-RUAG-Airbus DS- CFAO, Durham-NOVA and University of Galway-IoF), aiming at a complete concept for a correction chain for space applications.

9912-54, Session 10

FAME: freeform active mirror experiment

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FAME stands for Freeform Active Mirror experiment. It is a four-year project and part of the OPTICON/FP7 programme. It aims at providing a breakthrough component for future compact, wide field, high resolution imagers or spectrographs, based on both freeform technology and the flexibility and versatility of active systems.

Due to the opening of a new parameter space in optical design, Freeform Optics are a revolution in imaging systems for a broad range of applications ranging from high tech cameras to astronomy, via earth observation systems, drones, defense.

Freeform mirrors are defined by a non-rotational symmetry of the surface shape, and the fact that the surface shape cannot be simply described by conicoids extensions, neither off axis conicoids. An extreme freeform surface is a significantly challenging optical surface, especially for UV/VIS/NIR diffraction limited instruments. Some of these exotic surfaces are already proposed and used on-sky, such as the recombination surfaces of the PIAA apodiser.

The aim of the FAME effort is to use an extreme freeform mirror with standard optics in order to propose an integrated system solution for use in future instruments. The work done so far concentrated on identification of compact, fast, wide field optical designs working in the visible, with a diffraction limited performance; optimization of the number of required actuators and their layout; the design of an active array to manipulate the face sheet, as well as the actuator design.

In this paper we present the status of the demonstrator development, with focus on the different building blocks: an extreme freeform thin face sheet, the active array, a highly controllable thermal actuator array and the metrology and control system.

9912-55, Session 10

Novel and efficient ADC concept for BlackGEM telescope

Rik ter Horst, Jan W. Kragt, ASTRON (Netherlands); Dirk Lesman, NOVA Optical Infrared Instrumentation Group (Netherlands)

Earth base telescopes suffer from atmospheric dispersion caused by refraction of light through the atmosphere. For high quality astronomical observations dispersion should be corrected to a level where the spectral shift is virtually eliminated. A common practical solution is a combination of two counter rotating wedge shaped lens combinations for a step-less correction of all Zenith angles in the desired range. Drawbacks of this solution are high complexity of the optical elements, the required extra space and added mass and a mechanism with control electronics.

A novel solution has been found where the ADC function is integrated in the three-lens corrector by optimizing radii and offsets. The result is a highly effective system where, without adding any extra optical component or sacrificing on image quality, atmospheric dispersion can be corrected for Zenith angles down to 70 degrees. The correction is done by lateral displacement of only one field corrector lens such that the introduced dispersion compensates the dispersion of the atmosphere. The concept is applicable for other optical systems having at least three lens elements used as a field corrector. This concept will be applied in the BlackGEM telescope array. The basic design of the BlackGEM telescope consists of a parabolic primary mirror, a spherical secondary and a three-lens field corrector (Harmer-Wynne configuration).

BlackGEM is a planned array of optical telescopes located at the La Silla astronomical observatory in Chile. The system is specifically designed to detect the optical counterparts from gravitational wave sources detected with Virgo and LIGO. The BlackGEM array will comprise at least 3 remotely controlled telescopes with primary mirrors of 650 mm diameter. Each telescope will be equipped with a 10500 x 10500 pixel detector of 9 micron pixel size. The 3300 mm focal length of the telescope leads to a sky sampling of 0.56"/pixel, well matched to the seeing on La Silla. BlackGEM's precursor and prototype, the Meerlicht telescope, will be located in South Africa.

The paper describes the optical trade-offs, design and optimization and the mechanical design and implementation of this novel ADC solution.

9912-56, Session 10

Multilayer active shell mirrors for space telescopes

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A novel active mirror technology based on carbon fiber reinforced polymer (CFRP) substrates and replication techniques has been developed. Multiple additional layers are implemented into the design serving various functions. Nanolaminate metal films are used to provide a high quality reflective front surface on the mirror. A backing layer of thin active material (piezoelectric/electrostrictive) is implemented to provide the surface-parallel actuation scheme. Printed electronics are used to create a custom electrode pattern and flexible routing layer. Mirrors of this design are thin (< 1.0 mm), lightweight (2.7 kg/m2), and have large actuation capabilities (> 100 ?m defocus amplitude). These capabilities, along with the associated manufacturing processes, represent a significant change in design compared to traditional optics. Such mirrors could be used as lightweight primaries for small CubeSat-based telescopes or as meter-class segments for future large aperture observatories. Multiple mirrors can be produced under identical conditions enabling a substantial reduction in manufacturing cost and complexity.

An overview of the design decisions and manufacturing processes will be presented here. Specifically, considerations related to material selection, sizing of the active layer, and accommodating multiple active channels will be presented here. Methods to reduce the as-manufactured figure error of thin composite shells will also be presented. Additionally, predictions on

the actuation performance of the Carbon Shell Mirrors have been made through finite element simulations. An optimized electrode pattern has been developed in order to generate astigmatic modes of deformation. Results show that correctabilities on the order of 250-300x can be achieved with only 41 independent actuators. Actuation strokes of 10-100 ?m PV are also achievable over low-order modes – a product of the ultra-thin design.

Characterizing thin, highly active mirrors presents a significant challenge due to 1) the relatively high magnitude initial figure error, and 2) the extremely large actuation capabilities. Traditional optical techniques have proven insufficient due to a lack of dynamic range. An outline of the custom metrology system used to characterize the Carbon Shell Mirrors will be presented. The system is based on a Reverse Hartmann test and can accommodate extremely large deviations in mirror figure (> 100 ?m PV) down to nanometer precision. The system has been validated against several traditional techniques including photogrammetry and interferometry. Closed-loop figure correction experiments have been performed with this apparatus on 150 mm dia. prototypes. The mirrors have demonstrated post-correction figure accuracies of 250 nm RMS (one dead actuator limiting performance). Current efforts are focused on reducing the initial figure error leading to diffraction-limited performance over visible wavelengths.

9912-57, Session 10

Advances in silicon carbide active and passive telescopes

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Recent advances in the fabrication processes of silicon carbide optics have resulted in the ability to produce lightweight mirrors and structures allowing for truly athermalized systems. Increased understanding of processing parameters and interactions have enabled these reaction bonded silicon carbide structures to be manufactured with less internal stress allowing for a reduction in generation times and improved yields. These improvements have been used to successfully manufacture the passive 0.5m primary used in the recent PICTURE-B payload on a NASA Black Brant IX sounding rocket. Assembly techniques are being incorporated that allow for individual components to be bonded together using similar, near identical compositional formulations thus eliminating the need to compensate for bond differences as one would observe in brazed components. Developing technologies in additive manufacturing of silicon carbide with "in family" properties relative to fugitive core cast materials have provided a new vehicle for manufacture of unique geometries which can be combined with more traditional parts through bonding to give the designer a wider range of practical options.

9912-58, Session 10

Orbiting rainbows: a granular imager

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"Orbiting Rainbows" is a Phase II NASA Innovative Advanced Concepts (NIAC) study that is looking twenty years into the future of creating a space-based observatory from granular media. "Granular matter" is considered to be the fifth state of matter; this investigation draws from recent research on disordered lenses and turbid lens imaging. The investigators are performing fundamental research and developing the technology roadmap to construct an optical system in space using nonlinear optical properties of a cloud of micron-sized particles, shaped into a specific surface by light pressure, to form a very large and lightweight aperture of an optical system. This "cloud optic" will be relatively simple to package, transport, and deploy. It is reconfigurable and can be re-targeted; the focal length is variable and it will be self-healing and ultimately disposable. The concept, in which the aperture does not need to be continuous and monolithic, will allow the aperture size to be several times larger than currently envisioned observatories such as ATLAST and a fraction of the mass and cost. The ultimate cloud optic could be several tens of meters in diameter, and multiple clouds can be combined to create kilometer-class apertures. The concept also relies heavily on computational optics to deconvolve objects from non-deal imagery. Simulations and experiments have been positive using speckle interferometry techniques together with blind image deconvolution using a sparse, specular media for a primary mirror of an optical system. This talk with give a brief overview of the Orbiting Rainbows concept and presents ground-based subscale experimental results.

9912-59, Session 10

Long-term stable active mount for reflective optics

Claudia Reinlein, Christoph Damm, Matthias Mohaupt, Andreas Kamm, Nicolas Lange, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

We report on the development of an active device/mount with orthogonal actuator matrix offering a stable shape optimization for gratings or mirrors. The design of the device is following a set-and-forget idea, meaning that it should remain constant after optimizing the position of the actuators and the shape of the optical element. We introduce the actuator distribution and show its capability to compensate for wavefront aberrations. Therefore, we calculate the accessible Zernike polynomials from the actuator influence function. Further, we will give results on the mechanical implementation. We use manual actuators to build a device with a reasonable price. In order to translate the stroke of the manual actuators, we introduce hinges that simultaneously pre-load the actuators. Therewith, we enable up-and downward movement of the optical element by the actuators.

Experimental tests show the capability of the device to compensate for aberration in two grating substrates. Thus we report on the interferometric measurements of the achievable best flat surface of 110x105 mm device and 220x210 mm device. The smaller device is used to take measurements of the position depending aberrations. Here we optimize the position in a vertically installed interferometer and repetitively measure the devices shape over several weeks. Then we bring the device to a horizontally installed interferometer and repeat these long-term measurements showing no position depending aberrations. Long-term measurements of the large device show similar results. We will particularly stress that the rms-shape remains constant within +/-3 nm rms during three month and for both devices.

Further, we will adress temperature-induced shape variations in order to update the thermo-mechanical model. Therewith we will discuss potential applications in space telescopes such as active mirrors, and Earth-based facilities where long-term stability is mandatory.

9912-60, Session 11

Multi-core fibers: the road to multimode photonics

Joss Bland-Hawthorn, Sergio G. Leon-Saval, Seong-Sik Min, Emma Y. Lindley, The Univ. of Sydney (Australia)

Photonic devices are finding increasing use in astronomical instruments: these include fibre bundles, laser combs, waveguides, fibre Bragg gratings, photonic lanterns, circulators and splitters. A major problem is that most devices developed for telecom operate only with single-mode fibres which are notoriously difficult to couple light into. We show that multi-core fibre technology can be used in place of multimode fibres and incorporate many photonic functions. The challenge here is to imprint uniform functions across all cores. We have built a Sagnac interferometer in order to mass produce the first high throughput multi-core devices, an essential step on the road to multimode photonics.

9912-61, Session 11

A micro-lens array based pupil slicer and double scrambler for MAROON-X

Andreas Seifahrt, Julian Stürmer, Jacob L. Bean, The Univ. of Chicago (United States)

We report on the design and construction of a micro-lens array (MLA)-based pupil slicer and double scrambler for MAROON-X, a new fiber-fed, red-optical, high-precision radial-velocity spectrograph for the 6.5m Magellan Telescope in Chile. We compare various design concepts and alignment strategies and show test data for different types of MLAs. Our final device uses two MLAs to slice the pupil projected from a f/3 100um octagonal fiber in three parts and feeds them at f/5 into three 50x150um rectangular fibers, effectively combining a pupil slicer with a double scrambler design.

9912-62, Session 11

Fiber mode scrambler experiments for the Subaru Infrared Doppler Instrument (IRD)

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We report the results of fiber mode scrambler experiments for the high-precision radial-velocity (RV) instrument for the Subaru telescope. The instrument, IRD, is a fiber-fed, near-infrared spectrometer with an Echelle grating and combined with a laser frequency comb. IRD can get high-resolution (R~70000) spectra from 0.97 to 1.75 ?m and its main purpose is to search for habitable exoplanets around late-M dwarf stars. The flux distribution of late-M dwarfs has a peak at near-infrared wavelengths, so high-dispersion spectrometer working at near-infrared wavelengths is necessary. Searching for planets around low-mass stars has several advantages. (1) RV change of low-mass stars by planets orbiting around the star is larger than that of solar-like stars. (2) Habitable Zone (HZ) of low-mass stars is closer to the stars due to its low-luminosity. These make planets in HZ around low-mass stars easier to be detected. IRD's expected accuracy of the radial velocity measurement is ~1m/s and with this accuracy planets in HZ around late M-stars can be detected.

It is mandatory to reduce the modal noise in order to achieve ~1m/s accuracy.

The modal noise is an instability of phase and amplitude distributions of light emerging from a multi mode fiber and is caused by interference of many propagating modes of light. Multi-mode fiber has many propagating modes of light and interference of these modes makes speckle pattern. This pattern is very unstable and varies by change of optical fiber's stress, temperature, and so on. This speckle pattern change is called the modal noise and produces fake signals of RV change and reduces the accuracy of RV measurements. The modal noise is larger with narrow-bandwidth light source because narrow-bandwidth light produces small number of propagation modes. At near-infrared wavelengths the modal noise is larger than at visible because the number of propagating modes of light is smaller.

We have systematically tested many kinds of mode scramblers to reduce the modal noise by averaging energy distribution of propagation modes at near-infrared wavelengths. We need 2 mode-scramblers for star and for laser frequency comb. Mode-scrambler for comb needs greater scrambling effect because bandwidth of laser is narrower than that of absorption line of star, but low efficiency is permissible. On the contrary, scrambling for star is easier because bandwidth of absorption line is broad and atmospheric seeing works as a scrambler. However, it needs high efficiency. We mainly report effects of mode scrambler for star.

We have compared both static and dynamic scramblers with narrow and broad bandwidth light sources and deformable mirror to simulate seeing condition. The effect of the static scrambler includes the fiber-length dependence, double scrambler, octagonal fibers, and the fiber-twining. Dynamic scrambler is devised to move fibers dynamically and yields time averaged light without the modal noise.

9912-63, Session 11

12.5-GHz-spaced laser frequency comb covering Y, J, and H bands for infrared Doppler instrument

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In order to detect Earth-like planets around nearby red dwarfs (in particular late-M stars), it is crucial to conduct precise radial velocity (RV) measurements at near-infrared wavelengths where these stars emit most of the light. We have been developing the Infrared Doppler (IRD) spectrograph covering the wavelength from 0.97 to 1.75 ?m for the Subaru telescope. To achieve 1m/s RV measurement precision, we employ our original laser frequency comb (LFC) with a wide-wavelength coverage in the near-infrared as an extremely stable wavelength standard.

Our LFC has been developed based on a novel multi-gigahertz-spaced comb generation technology employing a frequency stabilized laser diode, an optical pulse synthesizer (OPS) and a highly nonlinear fiber (HNF). The seed comb generated from a hydrogen-cyanide stabilized laser at 1549 nm is input into the OPS consisting of an arrayed waveguide grating and 30 output channel waveguides each having intensity and phase modulators. A picosecond pulse train with a repetition frequency of 12.5 GHz synthesized by the OPS is amplified by an EDFA and is compressed to enhance the peak power up to more than 700 W. Finally, it is launched into the HNF to generate the 12.5-GHz-spaced LFC. Our LFC generator has some advantages including simple and easy frequency stabilization, all fiber-optic configuration, and broadband calibration by the frequency shift of all modes in the LFC. However, it was not easy to broaden the comb spectrum since the pulse peak power was not quite high due to the high repetition rate. We have found that a configuration of two kinds of spliced HNFs with different dispersion wavelengths is effective for broadening the comb spectrum toward shorter wavelength compared to a single HNF configuration.

We have successfully generated a 12.5-GHz-spaced comb ranging over 700 nm from 1040 to 1750 nm, almost covering Y, J, and H bands as the atmospheric windows. The frequency stability was measured by optically heterodyning the comb with an acetylene-stabilized laser at 1542 nm as a reference light. The LFC showed a frequency stability of less than 0.2 MHz and an almost constant spectrum profile for 6 days. The noise of the comb modes was evaluated by optically heterodyning the comb with another

continuous-wave laser. The comb showed a high contrast of about 35 dB.

The LFC has much stronger intensity than star light and its spectrum has full of ups and downs. Furthermore, it has a high degree of polarization and high coherence that induces speckle noise after the multimode-fiber propagation. Since these characteristics degrade the spectrograph performance, we have developed wavelength independent optical processing components including an optical power attenuator, a spectrum equalizer, a depolarizer, a speckle reducer and a mode scrambler for multimode fiber transmission.

We have also achieved a novel calibration system for astronomical spectrographs by introducing an optical frequency shifter in our LFC generator. The optical frequency shifter induces a precise frequency shift of around 40 MHz for all spectral comb lines, which is helpful for the spectrograph calibration over a wide wavelength region.

9912-64, Session 11

Design of real-time measurement for optical fiber positioning based on FPGA

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In order to track the stellar objects in fiber spectroscopic telescopes, measuring the fiber positions is necessary, which is currently unsolved due to the large number of data. Field Programmable Gate Arrays (FPGA) is an integrated circuit designed to be configured by a customer or a designer after manufacturing, and it is convenient to achieve an image processing system based on parallelism and pipeline technology with FPGA, hence the FPGA based imaging processing method as a newly arisen technique owns unparalleled advantages in high-speed image processing system over the conventional ones based on Central Processing Unit (CPU), Graphics Processing Unit (GPU), Application Specific Integrated Circuit (ASIC) etc.. In this paper, we design a novel real-time fiber position measure system based on FPGA. The large-scale distributed parallel calculation is fulfilled in the embedded system, and the real-time threshold segmentation, the labeling of connected domain and the feature extraction for the high-speed data stream are completed during the data transmission, thus the large number of data can be transformed into less information of image feature. To be specific, the system consists of the data acquisition module, the image processing module and the image display module. At first, a high speed digital camera is employed for the image acquisition. Next, in particular, the spot detection, which is affected directly by the detection algorithm and realization mode, is the key part of the image processing module. In this system, data stream structure model based on feature transmission is utilized to extract the feature of connected domain with parallel data, and the distributed calculation based on the feature of the connected domain includes a hardware accelerating structure based on a multi-dimensional pyramid, which is designed for global searching and labeling of the connected domain. After the processing, the coordinate data calculated by a digital signal processor (DSP) and the processed images are output to peripheral devices for the display, moreover, a Microcontroller Unit (MCU) is an alternative for the system to implement additional process. As a result, with the test system, the fiber spot detection can be finished at 50 f/s for 4k 4k pixel images, and the detection error is within 1% pixel, which proves the system we design is feasible for the precise and real-time measurement of the optical fibers.

9912-65, Session 12

Modal noise suppression in the NIR region using multicore fibre and photonic lanterns

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Exoplanet detection is one of the fast-growing areas of astronomical research. A strong drive to detect habitable Earth size planets is underway, with a number of new instruments due to come on-line in 2016. Many of these instruments operate in the near-infrared (NIR) band and use the radial-velocity method (detection of host star absorption-line Doppler shifts), to measure radial velocity shifts of the order of 1 m/s or less. This requires a very stable NIR high-resolution spectrograph and, if fibre coupled, a very stable fibre feed. However light propagation in multimode optical fibres is not inherently stable and suffers from modal noise caused by quasi-random phase and amplitude variations in near- and far- field light distributions. This modal noise has been shown to critically limit the signal-to-noise ratio achievable in fibre-coupled, high-resolution spectrographs. Because modal noise becomes significantly worse with increasing wavelength and decreasing mode numbers, it presents a risk to the next generation of near-infrared precision radial velocity spectrographs being proposed for ELTs.

We are investigating new fibre technologies that can potentially solve the modal noise issues in the NIR region. The new technology that we present is a combination of a multicore fibre (MCF) and a photonic lantern (PL) specifically designed to provide highly efficient phase and amplitude scrambling in the NIR with a low mode count. We designed the multicore fibre to match the GIANO fibre core size and mode count when injected with an F/5 beam at a central wavelength of 1.64 ?m. The GIANO-laboratory spectrograph facility at Arcetri Observatory was used to measure the modal noise of the MCF-PL device and the GIANO test fibres for direct comparison of performance.

The preliminary results show that the MCF-PL device performs an order of magnitude better (in terms of modal noise reduction) than the equivalent circular multimode silica fibre. In this paper we give an overview of the specifications, design and manufacture of the multicore fibre and photonic lantern. We also present the initial modal noise test results for the MCF-PL and equivalent multimode circular fibre obtained with the GIANO laboratory spectrograph test facility.

9912-66, Session 12

Communication architecture for the fiber positioning system of the DESI fiber-fed spectrograph

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This paper presents a design solution for controlling the five thousand fiber positioners within the sensing plate of the DESI telescope. Each of these positioners is a robot which allows positioning its optic fiber with a resolution within the range of few microns. The high number and density of these robots poses a challenge for handling the communication from a central control device to each of these five thousand. Furthermore, an additional restriction applies as the required time to inform every robot of its desired position must be lower than a second. Additionally, a low energy consumption profile is desired.

The complexity of standard internet-based protocols would imply that most of the computational resources of each robot should be applied to the communication protocol, instead of the positioning process itself. However, several embedded system oriented communication protocols

are still available and are evaluated in this paper. The study has considered both wired and wireless protocols.

Among the wireless solutions, ZigBee and CyFi have been considered. The wireless approach implies that the communication channel is shared among the five thousand robots. The shared channel along with the distribution of the robots and the sensing plate lead to high interferences and delays in the transmission of the information. Using simulation tools these wireless protocols have been discarded as they do not allow achieving the requirements previously presented.

The studied wired protocols comprise I2C, CAN and Ethernet. These three protocols, and different combinations of them, have been studied and evaluated to determine their hardware requirements, computational complexity, communication time and power consumption.

The best solution is a hybrid multilayer architecture combining both Ethernet and I2C. A 1 Gbps Ethernet based network is used to communicate the central control unit with ten management boards. Each of these boards is a low-cost, low-power embedded device that manages a thirty six degrees sector of the sensing plate. Each of these boards receives the positioning data for five hundred robots and communicate with each one through a two layer multiplexed I2C channel. This proposal allows to communicate the positioning information to each of the five thousand robots in 0.08 s. The whole communication architecture has a power consumption of 35.5 W.

9912-67, Session 12

Taipan instrument fibre positioner and starbug robots: engineering overview

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TAIPAN, currently nearing completion, is a multi-object parallel-positioning fibre-optic spectrograph designed for the UK Schmidt Telescope at Siding Spring Observatory in northern New South Wales, Australia. The instrument will be used to perform galactic and stellar surveys across the whole Southern hemisphere sky, over a 5 year period. The fibre positioning portion of TAIPAN consists of a complete refurbishment of the UKST interior spider which replaces the 6DF serial positioning instrument used for the RAVE Survey. The TAIPAN Instrument Structure provides a stiff, low deflection, spider to interface the necessary support infrastructure to allow the Starbug Positioning Robots to operate, while maintaining a minimum obscuration of the incoming beam. The TAIPAN Spider Assembly, to support the Starbug Positioning Robot, requires a curved glass field plate, located on the telescope focal plane, on which they are adhered through pressure differential generated by a vacuum system. The glass field plate is a kinematically mounted optic providing the instrument with tip-tilt and focus capability. The TAIPAN Instrument contains a driven “bug catcher” assembly to allow adherence and removal of the Starbug to the glass field plate. The TAIPAN Fibre Positioner contains a uniquely designed connector plate consisting of a high density interface to the Starbug routing all electrical, optical, and vacuum services required for Starbug operation. The high density connector plate is motor driven to allow lift off and adherence of the Starbug Robot to the GFP. A metrology system consisting of video camera under closed loop control monitors the position of 900 metrology fibres. The metrology camera is located in the central hole within the UKST Primary mirror.

The Starbug Robot itself consists of concentric piezo-ceramic tubes fully integrated with all necessary electrical wiring, vacuum and external metrology. The TAIPAN Starbug design contains a single optical fibre for each astronomical source. The design has an on-board LED which illuminates three positional metrology fibres. The Starbug is a line replaceable unit, 300 mm in length, with a detailed assembly and quality control process.

To drive Starbugs TAIPAN involves significant design work in independent motion control software and electronics. Starbug motion is controlled by 60 processors managing four phases of a 400V, 100Hz waveform that are independently switched to the 2100 Starbug electrodes. Software determines the exact location of 300 observing fibres and simultaneously positions them on their respective targets with a tolerance of 5 ?m. A Starbug can move on its X and Y axes and can rotate on a point. This allows 300 Starbugs to move to their target position without collision.

In addition to undertaking the TAIPAN surveys, it will serve as a prototype for the MANIFEST fibre positioner system for the future Giant Magellan Telescope. The TAIPAN instrument is designed to use a complement of 300 Starbugs. The initial deployment of the instrument in 2016 will consist of 150 Starbugs.

9912-68, Session 12

High contrast imaging using a visible nulling coronagraph

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We present results of experiments undertaken with the visible nulling coronagraph testbed (APEP) at JPL to further development of high contrast coronagraphy using interferometric nulling and an array of spatial filters. This technology is especially suitable for implementing a coronagraph on centrally obscured and/or segmented telescopes. The advantage arises by use of a segmented deformable mirror (DM) in the interferometer and an array of spatial filters comprised of individual single mode fibers. This allows division of the telescope pupil into sub-apertures that can be nulled independently while a Lyot Stop can be used to reject parts of the pupil that are obscured. Thus segment gaps, spiders and central obscurations can be easily ignored for the purpose of nulling. The combination of the DM and spatial filters also leads to the formation of a 360 degree dark hole without the need of a second DM.

While nulling has been demonstrated in prior experiments, the use of a 2-D array of single mode fibers in combination with the nuller is unique and challenging. Early in our experiments we discovered that the fiber array installed in APEP was deficient in its role as a spatial filter. The lengths of the fibers were too short to enable sufficient filtering of cladding light. Single fiber experiments were conducted to measure the length of fiber necessary for extinction of cladding light to 10-4. The results indicated that fibers with length between 1 to 2 m would be needed. We therefore had to explore novel methods to fabricate a new fiber array with sufficiently long fibers while simultaneously ensuring that all the fibers were equal to within the criteria needed to produce a coherent wavefront for planet light (the nulling of starlight does not care about the coherence since nulling occurs independently in each fiber).

We adopted a dual-pronged approach of building a quick, incoherent fiber array to demonstrate and uncover issues with starlight nulling, while also building a coherent fiber array to be used for the final demonstration. Both arrays also presented the challenge of fabrication of microlenses. Each microlens had to be positioned to within +/- 0.5 um of the center of the corresponding fiber. Additionally, each fiber was potentially offset randomly from the ideal grid by +/- 10 um. We developed a measurement system that measured the fiber positions with the accuracy necessary for this purpose. We then had to develop a new microlens fabrication technique (thermal reflow of photoresist) because the traditional technique (etching of fused silica) could not meet the large microlens sag requirement. We fabricated, aligned and bonded microlenses to the incoherent array and conducted nulling experiments. The DM segments were used to match path lengths in the interferometer (necessary for phase control), while the fibers were used to match the amplitudes of the interfering beams. We were able to demonstrate mean contrast between 2x10-7 and 6x10-7. The contrast was limited mainly by instability of the intensity distribution of starlight in the pupil and possible polarization mis-match between the interfering beams.

9912-69, Session 12

Post-inscription tuning of multicore fibre Bragg gratings

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Fibre Bragg gratings are used in astronomy for their ability to suppress narrow atmospheric emission lines of temporally varying brightness before the light is dispersed. These gratings can only operate in a single-mode fibre as the suppressed wavelength depends on mode velocity in the core. Recent experiments with fibres containing multiple single-moded cores have demonstrated the potential for inscribing identical gratings across all cores in a single pass. We have already improved the uniformity of gratings in 7-core fibres via modifications to the writing process; further progress can be achieved by tuning the gratings of the outer and inner cores relative to one another. By coating the fibre in a heat-conductive material with a high expansion coefficient, we can harness the effects of temperature and strain on the spectral response of each core in order to make the entire fibre suppress one wavelength to a depth of 30 dB or greater.

In this paper we present methods and results from experiments concerning the post-write tuning of gratings in multicore fibres.

9912-70, Session 13

First results of tests on the WEAVE fibers

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WEAVE is a new wide-field spectroscopy facility proposed for the prime focus of the 4.2m William Herschel Telescope. The facility comprises a new 2-degree field of view prime focus corrector with a 1000-multiplex fibre positioner, a small number of individually deployable integral field units, and a large single integral field unit. The IFUs (Integral Field Units) and the MOS (Multi Object Spectrograph) fibres can be used to feed a dual-beam spectrograph that will provide full coverage of the majority of the visible spectrum in a single exposure at a spectral resolution of ~5000 or modest wavelength coverage in both arms at a resolution ~20000. The instrument is expected to be on-sky by 2017 to provide spectroscopic sampling of the fainter end of the Gaia astrometric catalogue, chemical labeling of stars to V~17, and dedicated follow up of substantial numbers of sources from the medium deep LOFAR surveys.

After a brief description of the Fibre System, we describe the fibre test bench, its calibration, and some test results. We have to verify 1920 fibres from the MOS bundles and 740 fibres from the mini-IFU bundles with the test bench. In particular, we present the Focal Ratio Degradation and throughput verification of some cables.

9912-71, Session 13

Echidna Mark II: one giant leap for 'tilting spine' fibre positioning technology

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The Australian Astronomical Observatory's 'tilting spine' fibre positioning technology has been redeveloped to provide superior performance in a smaller package. The new design offers demonstrated 2.8 micron RMS closed-loop positioning errors in ~10 s (excluding metrology overheads) and an improved capacity for open-loop tracking during observations. Throughput losses are shown to be reduced by lengthening spines while maintaining excellent accuracy. New low voltage piezo actuator technology has greatly simplified the control electronics design, allowing a highly modularised architecture and significantly reducing the relative size, mass and cost of the entire positioner system.

Tilting spine technology, also known as 'Echidna' technology, offers simultaneous positioning of hundreds to thousands of densely-packed optical fibres at a telescope's focal plane for the purpose of multi-object spectroscopy. A key benefit of the technology is a high target allocation yield, achievable due to each fibre's large and overlapped patrol area and small exclusion radius around its tip.

A redesigned spine motor has improved positioning performance while remaining true to Echidna's simple pivoting ball principle. The new design has a refined mechanism and uses miniature piezo elements that require signal amplitudes an order of magnitude smaller than before. Specialised electronics components can now be replaced with standard off-the-shelf devices that are readily available at a fraction of the cost. Each spine can now be given its own postage stamp sized drive circuit that is completely independent and able move the fibre in any direction at any time.

A closed-loop positioning accuracy of 2.8 microns RMS has been demonstrated over thousands of positioning cycles in the lab. Such small errors offer a chance to reduce fibre tilt losses by trading off positioning resolution with spine length. A representative example is presented where these losses are halved, while still achieving a positioning error better than 5 microns RMS and a target allocation yield of 94%.

This paper describes the concept, design and prototyping of this next generation Echidna technology, the exemplary results seen in a laboratory test system, and the many advantages on offer for future instruments. Prospects for further miniaturisation of the motor assembly are explored, along with ideas to utilise the same piezo actuators in the AAO's autonomous Starbug fibre positioner robots.

9912-72, Session 13

The Potsdam MRS spectrograph: heritage of MUSE and the impact of cross-innovation in the process of technology transfer

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After first tentative experiments to utilize astronomical instrumentation for the purpose of minimal invasive optical diagnostics in medicine we have been able to demonstrate that the technique of integral field

spectroscopy from Astronomy, applied to a microscope rather than to a telescope, is indeed capable to differentiate complex organic tissue on the basis of spatially resolved Raman spectroscopy. The new technique is orders of magnitude more efficient than the current state of the art in medical instrumentation, and it has great potential to revolutionize resection margin identification in cancer diagnostics and surgery. Based on these findings, we have launched a joint research program with clinical experts and industrial partners to develop an optimized fibre-coupled multi-channel spectrograph with a dedicated novel IFU for the purpose of a formal validation program in dermatology towards a future prototype for clinical applications. On the basis of the concept of modular and replicable spectrographs for MUSE, we have designed and built a modified spectrograph that, as opposed to its predecessor, is adapted to a telecentric fibre input and has an extended blue performance, but otherwise maintains the properties of high-throughput and excellent image quality over an octave of wavelength coverage with modest spectral resolution. We present the opto-mechanical layout and a new detector system. Owing to the immediate purpose of the experiment, the spectrograph is dubbed the Multiplex-Raman-Spectrograph (MRS). However, given the performance of the new system, and building on the successful concepts of replicable spectrographs and small series production, e.g. the MUSE and VIRUS instruments, we also envision to deploy copies for integral field and/or multi-object spectroscopy at astronomical telescopes. We stress the benefits of a partnership between Astronomy, other disciplines in academia, and industry as a win-win situation for the expensive development of instrumentation.

9912-73, Session 13

Taipan fiber feed and spectrograph: engineering overview

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TAIPAN, currently nearing completion, is a multi-object parallel-positioning fibre-optic spectrograph designed for the UK Schmidt Telescope at Siding Spring Observatory in northern New South Wales, Australia. The instrument will be used to perform galactic and stellar surveys across the whole Southern hemisphere sky, over a 5 year period. An AAO designed fibre optic cable is used to transmit light from each of the 150 Starbug Robots (with upgrade path to 300) to a custom designed slit as input to the TAIPAN Spectrograph. The TAIPAN Fibre cable is designed to minimize path length to the Spectrograph for maximum throughput while incorporating AAO's best practices for minimizing FRD within a fibre run. Presented is a discussion of the detailed design considerations of fibre cable and slit design.

The TAIPAN Spectrograph is a facility upgrade of the UKST 6DF Spectrograph used for the RAVE Survey. It completely replaces the 6DF spectrograph and is part of the complete TAIPAN Instrument package being delivered to the UKST in 2016. The TAIPAN Spectrograph is an AAO designed all-refractive 2-arm design. It delivers a spectral resolution of R>2000 over the wavelength range 370-870 nm. It contains completely custom optics and mechanical components starting with a 300 fibre slit assembly. The 300 fibre slit feeds a 5 element F1.75 collimator assembly with one aspheric surface. The collimator optics reside within individual lens cells that provide tip, tilt, and x, y alignment adjustment. Alignment is occurring on the AAO lens centering station. The beam from the collimator is split into two bands with the blue arm covering 370 to 592 nm and the red arm covering 580 to 870 nm. Two VPH gratings are provided by Kaiser Optical Systems. The beam splitter and VPH grating assemblies reside in kinematically mounted holder assemblies for alignment and the ability to accurately remove and replace from the spectrograph. Custom camera barrels and lenses feed semi-custom Spectral Instruments 1100s Dewar Detectors. The red and blue cameras are F1.5, each a five element design with three aspheric surfaces. The optical subassemblies interface to a monolithic spectrograph structure. All optics in the TAIPAN Spectrograph have been manufactured by Optimax. An overview the overall opto-mechanical design and assembly of the TAIPAN spectrograph will be presented.

In addition to undertaking the TAIPAN surveys, the TAIPAN Spectrograph is part of a suite of upgrades to the UKST that are serving as a prototype for the MANIFEST fibre positioner system for the future Giant Magellan Telescope. The TAIPAN instrument is designed to use a complement of 300 Starbugs. The initial deployment of the instrument in 2016 will consist of 150 Starbugs.

9912-74, Session 13

On-sky performance evaluation and calibration of a polarization-sensitive focal plane array

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The advent of pixelated micropolarizer arrays (MPAs) has facilitated the development of polarization-sensitive focal plane arrays (FPAs) based on charge-coupled devices (CCDs) and active pixel sensors (APSs), which are otherwise only able to measure the intensity of light. Polarization sensors based on MPAs are extremely compact, light-weight, mechanically robust devices with no moving parts, capable of measuring the degree and angle of polarization of light in a single snapshot. Furthermore, micropolarizer arrays based on wire grid polarizers (so called micro-grid polarizers) offer extremely broadband performance, across the optical and infrared regimes. These devices have potential for a wide array of commercial and research applications, where measurements of polarization can provide critical information, but where conventional polarimeters could be practically implemented. To date, the most successful commercial applications of these devices are 4D Technology's PhaseCam laser interferometers and PolarCam imaging polarimeters. Recently, MPA-based polarimeters have been identified as a potential solution for space-based telescopes, where the small size, snapshot capability and low power consumption (offered by these devices) are extremely desirable. In this work, we investigated the performance of MPA-based polarimeters designed for astronomical polarimetry using the Rochester Institute of Technology Polarization Imaging Camera (RITPIC). We deployed RITPIC on the 0.9 meter SMARTS telescope at the Cerro Tololo Inter-American Observatory and observed a variety of astronomical objects (calibration stars, variable stars, reflection nebulae and planetary nebulae). We use our observations to develop calibration procedures that are unique to these devices and provide an estimate for polarimetric precision that is achievable.

9912-75, Session 14

Fabrication of a wide-field NIR integral field unit for SWIMS using ultra-precision cutting

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Recently an observational technique called integral field spectroscopy (IFS) has been extensively used in astronomy. It enables us to obtain a three-dimensional data cube (x, y, ?), i.e. spatially resolved spectrum in a single exposure. In the context of increasing importance of IFS, we have been developing a new near-infrared integral field unit (IFU) for SWIMS (Simultaneous-color Wide-field Infrared Multi-object Spectrograph), which we call SWIMS-IFU. SWIMS will be mounted on University of Tokyo Atacama Observatory (TAO) 6.5-m telescope as one of the 1st generation instruments, and planned to be installed on Subaru 8.2-m telescope for verification and initial science observations in 2016.

Concept of SWIMS-IFU is simple: To realize IFS observation readily, we develop a compact and lightweight IFU and set it on a focal plane in a conventional multi-slit spectrograph, thus it can be remotely selected and exchanged like a slit mask. The IFU works as a connector between a telescope and the spectrograph by converting 2-D image of FoV into 1-D pseudo-long slits in the same way as so-called "Advanced Image Slicer" configuration. We apply this concept to SWIMS.

SWIMS-IFU appends a capability of IFS to SWIMS which was originally designed as an imager and multi-slit spectrograph. In the current design, we can switch observational modes (imaging, MOS and IFS) easily and quickly during an observing night.

SWIMS-IFU provides entire near-infrared spectrum from 0.9 to 2.5 micron simultaneously with wider field of view of 17.2" x 12.8" compared with current existing near-infrared IFUs. This capability allows us to carry out high-efficiency IFS observations with SWIMS. Its basic parameter and optical design were reported in the previous proceeding (Y. Kitagawa et al., 2012).

In this presentation we describe a method for fabrication and measurements of optical surfaces and support structures of SWIMS-IFU. We specially make consideration for designing support structures as the IFU has tight restriction on both size (< 60 mm x 170 mm x 220 mm) and weight (< 0.8 kg) to be installed and handled with the mask-exchanger unit of SWIMS. All the components of the IFU are made of special aluminum alloy which has the same thermal expansion coefficient as an electroless nickel-phosphorus. This enables us to achieve high-quality surface finish on the Ni-P coating easily without thermal strain between the alloy and the coat under cryogenic condition. We adopt an ultra-precision cutting technique to monolithically fabricate mirror arrays such as an image slicer, which have complicated shapes and many facets. Each facet is created by shaper cutting process with a single crystal diamond tool. The measurement results show that the surface roughness is less than 10 nm r.m.s. and satisfies our requirements. This method considerably reduces alignment procedure of optical elements. When increasing number of elements, monolithic fabrication has also an advantage to shorten processing time with keeping good repeatability. It will be useful for a multi-object IFS facility such as a 2nd generation instrument for TMT.

9912-76, Session 14

Stop-less Lyot coronagraph for exoplanet characterization: first on-sky validation in VLT/SPHERE

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The VLT/SPHERE instrument includes a unique long-slit spectroscopy (LSS) mode coupled with Lyot coronagraphy dedicated to the spectral characterisation of directly imaged giant exoplanets. The performance of this mode is limited by its non-optimal coronagraph, but in a previous work we demonstrated that it could be significantly improved at small inner-working angles using the stop-less Lyot coronagraph (SLLC). A prototype of the SLLC was installed in VLT/SPHERE in 2014 during the reintegration of the instrument in Paranal, and it was extensively tested in 2015 to characterise its performance. The performance is tested in both imaging and spectroscopy using data acquired on the internal source of SPHERE. In imaging, we obtain a raw contrast gain of a factor 10 at 0.3" with the SLLC. We also demonstrate that no Lyot stop is required to reach the full performance, which validates the SLLC concept. Comparison with a realistic simulation model shows that we are currently limited by the internal phase aberrations of SPHERE. In spectroscopy, we obtain a gain of ~1 mag in a limited range of angular separations. Simulations show that although the main limitation comes from phase errors, the performance in the non-SLLC case is very close to the ultimate limit of the LSS mode. We present the very first on-sky data with the SLLC, which appear extremely promising for the future scientific exploitation of an apodized LSS mode in SPHERE. Finally, we explore a new possibility for the speckle subtraction in the LSS mode that could significantly improve the data analysis with respect to methods based on spectral differences.

9912-77, Session 14

Development of an efficient photonic device for the reformatting of celestial light

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The advent of 30 m class Extremely Large Telescopes will require spectrographs of unprecedented spectral resolution in order to meet the ambitious science goals of such telescopes, for example the detection of Earth-like exoplanets via the radial velocity technique. The consequent increase in the size of the spectrographs makes it challenging to ensure their optimal environmental stabilisation and precise spectral calibration. Currently, multimode (MM) optical fibres transport light from the telescope focal plane to the spectrograph housed in a separate environmentally-stabilised facility. However, the use of MM fibres introduces "modal noise", which manifests as variations in the light pattern at the output of the fibre as the input coupling and/or fibre position changes. These variations degrade the spectrograph line profile, thereby reducing the precision of the instrument.

The "photonic lantern" is a guided-wave transition that efficiently couples a MM Point Spread Function (PSF) into an array of single modes (SM). Recent developments have shown that they can, in principle, generate a spectrograph input free of modal noise by reformatting the output SMs into a linear array. Placed at the input to a spectrograph, this pseudo-slit is diffraction-limited in the dispersion axis and hence free of modal noise, whilst also minimising the instrument size in the plane of dispersion.

In 2013 we developed the "photonic dicer", a monolithic device that seamlessly integrated the photonic lantern and reformatting functions to produce such a pseudo-slit. They were manufactured using the direct-write technique of Ultrafast Laser Inscription (ULI) to inscribe waveguides into a glass substrate. These devices exhibited an in-laboratory throughput of ~65 % and an on-sky throughput of ~20 % for H-band light from the

CANARY Adaptive Optics (AO) system on the William Herschel Telescope (WHT). While this proved the feasibility of using them on-sky, additional work was required to accurately mode-match the input with the telescope PSF and to integrate the device with a MM relay fibre. However, the interface between the MM fibre and the MM waveguide of an integrated device can cause additional modal noise when these components are not mode matched, which results in the coupling losses at the interface being strongly wavelength dependent.

In this paper we describe the fabrication and throughput performance of the "hybrid reformatter", which we propose as a solution to this problem. It combines the proven low-loss performance of a multicore fibre-based photonic lantern with a ULI manufactured three-dimensional waveguide interconnect that performs the reformatting function to a diffraction-limited pseudo-slit. We report on the in-laboratory throughput of the hybrid reformatter, and compare this to the throughput achieved on-sky at the WHT.

9912-78, Session 14

Modal noise characterisation of a hybrid reformatter

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The use of single-mode fibres in high-precision Doppler spectrographs has become very attractive: not only can they provide a stable point-spread-function and an absence of without modal noise, but they also allow for the use of a smaller spectrograph with the associated cost and complexity benefits. However, a major obstacle in using single-mode fibres on seeing-limited telescopes is inefficient coupling of light into the fibre.

Photonic lanterns can overcome this limitation, and enable the efficient coupling of incoherent multimode light to an array of single-modes. The most efficient types of photonic lantern demonstrated to date are made from multicore fibre, but they do not allow the output of the device to be arbitrarily reshaped. To address this shortcoming we made the hybrid reformatter -- a device which merges a multicore-fibre photonic lantern with a slit-reformatting device inscribed by an ultrafast laser. The reformatter reshapes the 2-D array of single-mode cores (the output of the multicore-fibre photonic lantern) into a 1-D array of single-mode waveguides, forming a slit-like structure suitable for input to a single-mode spectrograph. The device output is single-mode across the slit, i.e. in the spectrograph dispersion axis, and highly multimode along the slit.

Here we report the testing of a hybrid reformatter for modal noise by measuring device throughput at high spectral resolution and assessing the stability of the output point-spread-function under different injection conditions. This hybrid device operates around 1550 nm wavelength, supports 92 modes, and has a circular input 45 microns in diameter and a rectangular output measuring 6.2 microns x 570 microns. We demonstrate that the point-spread-function at the output of the hybrid device did indeed behave as a single mode across the slit and that no presence of modal noise was found.

9912-79, Session 14

A laser-locked white-light etalon calibrator for MAROON-X

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We report on the development, construction, and testing of a vacuum-gap Fabry-Perot etalon calibrator. Our etalon comb is based on a tightly temperature and pressure controlled bulk etalon with a finesse of 40 and a FSR of 15GHz, well suited for high-resolution astronomical spectrographs. White light from a fiber fed laser-driven light source is used to form a bright etalon comb spanning 500-900nm. A tunable laser scans the etalon and several transitions of atomic rubidium, providing a means to precisely align, trace and, if desired, lock the etalon to NIST traceable frequency standard. Our etalon crucially differs from other, similar systems. We use a single mode fiber to simultaneously feed laser and white light into the etalon, thereby removing any illumination-depended effects and guaranteeing the laser and white light to share the same mode volume in the etalon. We will discuss various implementations of how to separate white light and laser light with minimal loss of bandwidth for the etalon comb. We show a long-term stability of the etalon comb in the cm/s domain and discuss intrinsic limitations and future improvements. Where appropriate, we have used off-the- shelf, commercial components with proven long-term performance to accelerate the development timescale of this instrument. We demonstrate a turn-key system, ready to be installed at any astronomical observatory. The technology development shown here solves one of the key technical issues that stands in the way of constructing a radial velocity spectrograph capable of finding Earth-mass, habitable-zone exoplanets around Sun-like stars and low-mass M dwarfs.

9912-80, Session 15

New grating concepts in the NIR and SWIR spectral band for low and high resolution earth-observation spectrometers

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The resolution of a spectral apparatus is directly proportional to the angular dispersion of the applied dispersive element, e.g. a grating, times its illuminated cross section L. Consequentially, typical applications demand for two different types of grating layouts depending on the required spectral resolution. On the one hand, there are low-resolution blazed gratings with a period significantly larger than the addressed operational wavelength and which work near normal incidence. On the contrary, high resolution spectrometers often operate using binary gratings with a period smaller than the addressed wavelength range and which work under Littrow conditions. Our contribution here is twofold and covers both scenarios. We will report about our latest achievements to realize the essential dispersive elements during the breadboard activities of FLEX and CarbonSat missions; both announced within the framework of ESA's earth observation program.

The CarbonSat instrument uses a fused-silica GRISM (grating-prism) element in the high resolution SWIR-1 spectral channel. In order to meet the system's specification (diffraction efficiency >70%, polarization sensitivity <10%) while simultaneously decreasing the risk for a technological realization, our approach is the following: First, we have successfully established a high refractive index conformal coating with a

purposely designed nanolaminate made of titanium dioxide and aluminum dioxide. This coating is applied by atomic layer deposition onto a backbone fused silica grating which was fabricated by electron beam lithography (EBL) and deep reactive ion etching (DRIE). The aspect ratio (structure height to width) of the final element approaches 1:10. This value is still significantly smaller as compared to a pure fused silica grating necessary to fulfill the same optical specifications. The measured diffraction efficiency of the best realized elements are well above 75% with a polarization sensitivity of at most 5%. Finally, the grating substrate of size 120mm x 66mm is combined with the prism by plasma activated direct bonding such that no adhesion layer remains between both specimens. A specific mechanics was constructed for this purpose and we were able to achieve alignment accuracies better than 1 mrad.

The low-resolution channel of the FLEX instrument operates in VIS-NIR region. Here the challenges for the realization of a dispersive grating mainly lie within the large spectral bandwidth of 300nm. In order to guarantee high diffraction efficiency throughout the entire bandwidth, our technological realization approach is based on a so-called binary blazed grating. Here, a grating of uniform depth with varying lateral features was designed and fabricated by EBL and DRIE in fused silica. In order to minimize the polarization sensitivity and to relax the technological realization difficulties, some of the grating trenches were transformed into rectangular pillars with a two-dimensional cross section. Thus, the smallest realized features within the grating are about 140nm in width and 1700nm in depth. The measured diffraction efficiency was larger than 75% throughout the entire spectral region between 500nm to 800nm.

Both concepts offer a significant extension of the available design freedom for the realization of a great variety of high-performance gratings for different spectroscopic instruments.

9912-81, Session 15

Characterizing the cross dispersion reflection gratings of CRIRES+

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High resolution Infrared spectroscopy has many important applications in astrophysics from exoplanets to cosmology. Yet, almost all currently existing infrared spectrographs are limited by the rather small wavelength range which can be simultaneously covered.

The CRIRES+ project attempts to upgrade the CRIRES instrument which has been in operation at one of the VLT observatory (Cerro Paranal, Chile) 8 m Unit telescopes until July 2014. This will turn CRIRES+ into a fully operational cross dispersed echelle spectrograph with a simultaneous recording of 8-10 diffraction orders. CRIRES+ will provide a spectral resolving power of R = 100,000 over a usable wavelength range of (0.95 – 5.2) μm.

One of the main design goals of the upgrade project is to at least maintain or to increase the overall throughput of the instrument. To achieve this ambitious goal, all components will be optimized for their task and rigorously tested before integration.

In order to transform the CRIRES instrument into a multi-order cross-dispersed echelle spectrograph, a set of six reflection gratings, each one optimized for one of the wavelength bands CRIRES+ will operate in (YJHKLM), will be used as cross dispersion elements in CRIRES+. Due to the upgrade nature of the project, the choice of gratings depends on the fixed geometry of the instrument. Thus, custom made gratings would be required to achieve the ambitious design goals. Custom made gratings have the disadvantage, though, that they come at an extraordinary price and with lead times of more than 12 months. To mitigate this, a set of off-the-shelf gratings was obtained which had grating parameters very close to the ones being identified as optimal. To ensure that the rigorous specifications for CRIRES+ will be fulfilled, the CRIRES+ team started a collaboration with the national metrology institute of Germany PTB to characterize gratings under conditions similar to the operating conditions in CRIRES+ (angle of incidence, wavelength range).

The respective dedicated test setup was designed in collaboration between PTB and the CRIRES+ consortium. It consists mainly of bulk optics and is operated at room temperatures. The PTB provided light sources and detectors as well as a calibrated reference reflective sample for each wavelength range. With this setup, it is possible to measure the relative diffraction efficiency of the gratings both wavelength dependent (nine different wavelength equally distributed in each band) and polarization state dependent (the setup is equipped with a polarimetry unit based on wire-grid type polarizers) in a wavelength range from (0.9 to 6.0) μm.

We will present in this paper a description of the test setup, including a discussion of the lessons learned, and the test results on a set of off-the-shelf gratings. In addition to this paper, a summary paper giving a status update on the project and other more detailed papers on dedicated sub-systems of CRIRES+ will be presented by other members of the CRIRES+ consortium.

9912-82, Session 15

Final design and choices for EUCLID NISP grism

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The ESA mission Euclid is designed to explore the dark side of the Universe and to understand the nature of the dark energy responsible of the accelerated expansion of the Universe. Its objective is to map the geometry of the dark Universe by investigating the distance-redshift relationship and the evolution of cosmic structures. The NISP (Near Infrared Spectro-Photometer) is one of the two Euclid instruments operating in the near-IR spectral region (0.9-2?m). The NISP instrument has two main observing modes: the photometric mode, for the acquisition of images with broad band filters, and the spectroscopic mode, for the acquisition of slitless dispersed images on the detectors. The spectroscopic Channel uses four low resolution grisms to cover two spectral ranges: three "red" grisms for 1250-1850nm range, with three different orientations, and one "blue" grism for 920-1300nm range. The NISP grisms are complex optical components that combine four main optical functions: a grism function (dispersion without beam deviation of the first diffracted order) done by the grating on the prism hypotenuse, a spectral filter done by a multilayer filter deposited on the first surface of the prism to select the wavelength bandpass, a focus function done by a curved surface where the filter is

deposited and a spectral wavefront correction done by the grating nor parallel, neither straight grooves. This specific grating is made thanks to a new technic developed with SILIOS Technologies company to manufacture a resin-free grating with curved groove paths. The optical component is glued onto a mechanical ring, designed to survive to 60g load DLL and to keep optical performance at 130K. The design and manufacturing of these components represent an important challenge in order to obtain the best performance possible with very constraining requirements in particular for transmitted wavefront error quality. We will present the performance obtained on scale one prototypes of the filter, the grating and the mount manufactured to validate the final design choice and used to make the necessary trade-off during the development phase. All the prototypes manufactured have shown very good optical performances and have withstand vibrations and vacuum cryogenic test that confirms the feasibility of NISP grisms and prepare the next phase of the project for the procurement and test of NISP grism flight models.

9912-83, Session 15

Carbon nanotube coated petal-shape masks to suppress reflections in space-based telescopes

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A broad class of on-axis telescopes, which simultaneously transmit and receive, require suppression of the reflected light from the secondary mirror. For instance, an on-axis design of the optical telescope for the evolved Laser Interferometric Space Antenna (eLISA), a re-scoped version of the baseline LISA mission concept, fits in this category. If operated for this application, the telescope requires suppression of the directly reflected laser source from the secondary mirror of the telescope assembly back onto the detector. A simple circular hole or black spot on the secondary mirror as a means of suppressing the reflected light produces a bright (Poisson) spot on the detector due to diffraction from the edges of the hole or spot, defeating the purpose. To eliminate this diffraction effect, earlier work has shown that petal-shape mask designs based on hypergaussian functions could suppress the retro-reflected light intensity by several orders of magnitude.

However, when applied to a reflective surface, a suitable level of 'darkness' and low surface roughness in addition to the shape of the petal-shaped mask is required for good suppression. In this work, we lithographically fabricated an assortment of petal-shaped masks on silicon wafers and investigated growing carbon nanotubes (CNT) on the surface of the masks. The CNTs have been shown to be exceptionally good absorbers. They also provide an order-of-magnitude improvement over current absorptive surface treatments. We report on the challenges and technical difficulties of growing multiwalled carbon nanotubes on the surfaces of petal-shape masks on thin reflective substrates. The CNT growing process involves exposure of the reflective wafer imprinted with the petal masks to a 750-degrees Celsius environment in a furnace. Common reflective metals such as aluminum and silver, used in mirror fabrication, could not sustain the furnace heat. We discuss the process used to create these highly absorptive petal shapes. The final product is a reflective wafer with carbon nanotubes coated on the petal-shape areas only. Furthermore, we investigated the suppression capability of the petal-shaped masks in optical test beds subjected to incident laser sources of 532-nm and 1064-nm. An initial optical analysis of CNT coated masks on reflective substrates show 3-4 orders of magnitude intensity suppression relative to the incident laser source. The future application of this technology could be applied to variety of space-based telescopes requiring coronagraphs.

9912-95, Session P1

Revisiting static modulation in pyramid wavefront sensing

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The Pyramid Sensor (PS) is based on the Focault knife-edge test, yielding then, in geometrical approximation, only the sign of the wavefront slope. To provide linear measurements of the wavefront slopes the PS relies on a technique known as modulation, which also plays a central role to improve the linear range of the pyramid WFS, very small in the non-modulated case. In the main PS using modulation so far, this task is achieved by moving optical components in the WFS, increasing the complexity of the system. An attractive idea to simplify the optical and mechanical design of a pyramid WFS is to work without any dynamic modulation.

This concept was only merely described and functionally tested in the framework of MAD, and subsequently, with a holographic diffuser. The latter produce a sort of random distribution of the light coming out from the pupil plane, leading to sort of inefficient modulation, as most of the rays are focused in the central region of the light diffused by such device. The bi-dimensional original grating is, in contrast, producing a well defined deterministic distribution of the light onto a specifically shaped pattern. A crude option has been already discussed as a possibility, and it is here generalized to holographic plates leading to various distribution of lights, including a circle whose diameter would match the required modulation pattern, or more cost effective approaches like the one of a square pattern. These holographic diffusers would exhibit also zero-th and high order patterns and the actual size of the equivalent modulation would be linearly wavelength dependent, leading to colour effects that requires a careful handling in order to properly choose the right amount of equivalent modulation.

9912-96, Session P1

Multifunctional coating for the PROBA3 ASPIICS coronograph internal occulter

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We present the development status of a radially variable functional coating designed for the internal occulter of the ASPIICS (Association of Spacecraft for Polarimetric and Imaging Investigation of the Corona of the Sun) instrument. ASPIICS is the primary payload of the ESA PROBA-3 mission devoted to the in-orbit demonstration of precise formation flying for future European missions. The instrument is based on an externally occulted Lyot coronograph with the particularity of being distributed over two spacecrafts approximately 150 m apart. The internal occulter consists in a coating applied on the planar side of a plano-convex field lens; it features an opaque ring surrounded by a highly transparent outer ring and an inner clear aperture. The transmission is enhanced thanks to an antireflective coating stack whereas the occulting function over the ring is provided by a coating sharing layers with the former stack but absorbing light incoming from both sides of the lens-vacuum interface. The operational spectral range spans from 530 nm to 590 nm. The absorbing and antireflective coating stacks are metal-dielectric and dielectric-dielectric multilayers respectively all deposited using ion beam sputtering. They provide absorption higher or equal to 95% on both faces of the occulting ring and reflectivity lower or equal to 0.1% over the high transmission regions. Low reflectivity is required over the whole occulter

surface to minimize straylight.

One can divide the overall coating into four sub-stacks: the first one, in order of deposition, covers the whole lens planar surface and is at the same time constitutive of both antireflective and absorbing coatings. The second sub-stack is constrained to the occulting area and consists of additional layers that complete the absorbing coating for incidence from the lens material side. The third one, applied over the same area, forms the main part of the vacuum-side absorbing coating. Finally, the last stack, applied over the whole surface, completes both antireflective and vacuum-side absorbing coatings with its last layers providing protection against side corrosion for the metallic layers within the occulting ring. The optical designs of the different stacks are optimized simultaneously using a simulated annealing algorithm. The complex refractive indices for the design calculations were determined from the combination of variable angle spectral ellipsometric (VASE) and spectral transmittance measurements carried out on monolayers deposited on fused silica and silicon (100) substrates.

The proposed coating stack structure and the juxtaposition of antireflective and absorbing zones require a masking step during the application process in order to achieve the deposition of differentiating layers. UV projection photolithography involving a photoresist lift-off process is used to such purpose. The coating defects are characterized before and after the photolitographic process using scanning electron microscopy and digital optical microscopy. The vertical nano-roughness and lateral roughness of the interfaces between the occulting and transparent zones is characterized using phase-shift interferometry. Both spectral transmittance and reflectance of stack samples are measured and compared to simulations.

9912-97, Session P1

Progress on sol-gel antireflective coatings for astronomical optics

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Modern astronomical telescopes have a wide working wave band and large aperture. Multilayer, complex film structure would be needed for the demand of broadband antireflection with the method of vacuum evaporation which not has a high transmittance. Sol-gel coatings, on the contrary, have a better result only with several layers. In addition, there are many advantages of sol-gel coatings, such as simple technical control, better transmittance, large-area film formation. So a good application prospect of sol-gel coatings in the field of astronomical telescope is expected.

We have conducted some basic experiments about film formation, including the effects caused by various technology conditions on quality of film formation, for example, the proportion of each component, the aging time of sol, the speed of dip-coating, baking temperature etc. And the optimization and improvement on this basis. We also had the tests about environment endurance of the sol-gel coatings, including film hardness, friction resistance and hydrophobic property. Then we will concentrate on them and make improvement to gain a more steady performance film. We will continue to pay close attention on the relative optical properties such as optical constant, microstructure, contact angle, adhesive force and so on.

The technical test of small-aperture (about (100mm) lens have been finished, then we will increase the aperture of sample step by step to study the restriction on dip method and the possibility of replacement of film formation method. In the end. the double-side anti-reflective coatings for the meter-scale lenses, such as the Atmospheric Dispersion Corrector (ADC) for the KECK is expected. we have conducted some tentative verification tests and got an ideal result that the double-side transparency (300nm to 1100nm) is better than 97%.

9912-98, Session P1

J-Black: a stray light coating for optical and infrared systems

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Successful designs for scientific optical and infrared systems intended for wide dynamic range operation must include well defined stray light control to prevent noise contributions from unwanted radiation. Stray light control components, such as baffles, enclosures and structures require surface coatings that have minimum optical reflectivity and that are diffuse over the wavelengths for which the instrument is sensitive. Environmental conditions over the science mission life can provide similarly challenging physical requirements on stray light coatings.

A new stray light coating, called J-Black has been developed for NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA). The J-Black formulation stems from a series of trial coating runs at Puget Sound Coatings in Seattle. Combinations of commercially available aerospace grade coatings with selected additives, such as silicon carbide and glass spheres, were tried followed by optical and environmental testing. In July 2014, SOFIA participants worked with Lufthansa Technik personnel in Hamburg to apply J-Black to large areas of the SOFIA airborne telescope. The telescope is currently operated within the open cavity environment of the Boeing 747 platform aircraft.

Comparisons between J-Black reflectivity and other coatings commonly used for large area coverage, including two formulations of Ball Infra-Red Black, composites of Aeroglaze Z306 and Desothane CA8271F37038, demonstrate the new coating is among the lowest achieved for the 0.4 to 21 micron wavelength range. The J-Black coating is comprised of a combination of Nextel 3101, Nextel Primer 5523 and silicon carbide. A simple process has been developed to achieve a homogeneous complex surface structure which is needed for long wavelength applications. And while the process has numerous detailed steps, they are of short duration with minimal requirements for preciseness. Overall, the coating is relatively easy to apply and has been used on aluminum and composite materials. Tests with J-Black coated substrates demonstrate robust strength properties over the temperature range of -200C to +100C, including thermal shock and icing conditions and physical abuse via stiff brushing. Specular and diffuse reflectance performance measurements of J-Black coated samples were acquired using Surface Optics InspectIR-Vis which includes 4 filtered bands between 400 to 1100 nm. Long wavelength measurements using six filter bands covering 1.5 to 21 microns were made with a Surface Optics ET-100 Emissometer.

9912-99, Session P1

Atomic Layer Deposited (ALD) coatings for future astronomical telescopes: recent developments

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Atomic Layer Deposition (ALD) can create conformal, near stoichiometric and pinhole free transmissive metal fluoride coatings to protect reflective aluminum films. Spectral performance of astronomical mirror coatings strongly affect the science capabilities of future astronomical satellite missions. We are utilizing ALD to create a transmissive overcoat to protect aluminum film mirrors from oxidation. We desire high reflectance (> 80%) from the UV (~100 nm) to the IR (~2,000 nm). This paper summarizes the recent developments of ALD coatings on Al. Reflectance measurements, storage effects, film composition, film structure and future applications are discussed.

9912-100, Session P1

Astronomical large Ge immersion grating by CANON

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An immersion grating is a powerful optical device for the infrared high-resolution spectroscope.(Marsh et al.(2007),Kuzmenko et al.(2006)) Ge is the best material for a mid-infrared immersion grating because of Ge has very large reflective index (n=4.0). On the other hands, there is no practical Ge immersion grating under 5um use. It was very difficult for a fragile IR crystal to manufacture a diffraction grating precisely. Our original free-forming machine has accuracy of a few nano-meter in positioning and stability. We already fabricated the large CdZnTe immersion grating. (Sukegawa et al. (2012), Ikeda et al. (2015)) We are developing Ge immersion grating that can be a good solution for high-resolution infrared spectroscopy with the large ground-based / space telescopes. We succeeded practical Ge immersion grating with the grooved area of 75mm (ruled direction) x 19mm (groove width) and the blaze angle of 75 degrees. (CANON/Sukegawa et al. (2015)) The diffraction efficiency after HR and AR coating is over 70% at 4um which is almost same as theoretical value. A next generation large ground-based telescope will be required more large immersion grating. We are developing large Ge immersion grating for astronomy which has the grooved area of 155mm (ruled direction) x 40mm (groove width) and groove pitch of 91.74um. The typical performance are the spacing accuracy of <5nmRMS, the surface roughness of <2nmRMS and the surface irregularity of 80nm (PV) / 18nm (RMS). In this paper, we report performance of astronomical large Ge immersion grating, especially optical performance results. An apex angle of groove is very important to ideal efficient realization. Additionally, an optional apex angle can be achieved in Germanium by our process, we report on the theoretical efficiency of the apex angle and the actual efficiency compared with 85 degrees and 89 degrees.

9912-101, Session P1

The legacy of filter design and how that has extended into current choices for advanced astronomical filters

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In 1935 the single layer anti-reflective (AR) coating was invented by Alexander Smakula and patented by Zeiss. During that time SCHOTT also worked on AR coatings and filters based on interference due to multi-layers. Dr. habil. Walter Geffcken from SCHOTT invented a series of different coatings: metal dielectric interference filters (1939), (broad band) coatings with reduced surface reflections (1940), all dielectric interference filters with alternating high and low refractive index coatings (1942), and small bandpass interference filters based on multi-cavities (1944). These fundamental principles were invented by SCHOTT between about 1935 and 1945 and are still used in modern interference filter designs.

After World-War II this know-how was transferred to Mainz, West-Germany and further developed. In 2010 SCHOTT's interference filter know-how was bundled with the processing, polishing, and assembly know-how in Switzerland (Yverdon) now with more than 6200 square meter of coating space. These capabilities enable the complete design and manufacturing of high-tech cutting edge interference filters bringing the technology to its edge. In 2007 a study was performed for bandpass and blocking coatings for use in satellites.

Bandpass coatings in visible and NIR range are produced since 2008 for several space projects. With their FWHM bandwidth between 60nm to over 130nm, their very tight tolerance and a low defect requirement, theses filters are real challenges. Beside the bandpass filters, a black chrome coating has been developed to drastically reduce crosstalk and ghost image.

The projects were led together with SODERN who managed the assembly of the filters and took care of the space qualification of the filters. Despite the highly demanding tests, no change was observed in the spectral performance. Some of the produced butcher filters are currently operating above our heads in space.

Besides space coatings and filters for satellites in the orbit, steep edge narrow bandpass filters for ground based telescope instrumentations were developed fro CEFCA. The demanding requirements in terms of steepness, broad blocking range, center wavelength uniformity, center wavelength homogeneity, and transmitted wavefront error of the filter assembly pushed the filter design and the technology to its limits. A special developed white-light Shack Hartmann sensor enables the possibility to measure and reach the transmitted wavefront of the narrow bandpass filter who typically block light at 633 nm (measurement wavelength of state-of-the art wavefront systems). Such demanding filter requirements could only be reach by a combination of color glass (absorption filters) and interference filters based on special designs. As an example an H? filter (center wavelength of 660 nm) was manufactured with blocking range from 250 nm to 1050 nm with T < 10-5 (on average), FWHM bandwidth of 14.5 nm, and Tmax > 95 %. The transmitted wavefront error (RMS) was 0.07 lambda and the center wavelength uniformity over 100 mm x 100 mm filter size was below ±0.16 %.

9912-102, Session P1

Mid-infrared transmission gratings in chalcogenide glass manufactured using ultrafast laser inscription

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Ultrafast laser inscription is a versatile manufacturing technique which can be used to modify the refractive index of various glasses on a microscopic scale. This enables the production of a number of photonic devices such as waveguides, beam-splitters, photonic lanterns, and diffraction gratings. In this paper we report on the use of ultrafast laser inscription to fabricate volume phase transmission gratings in mid-infrared transmitting chalcogenide glass.

We describe the optimisation of the laser inscription process parameters to produce the best performing gratings and present theoretical models for expected grating performance. The first order diffraction efficiency of the gratings was measured, at mid-infrared wavelengths (3-5 ?m), and found to exceed 60% at the Littrow blaze wavelength, compared to a substrate external transmittance of 67%. This impressive result implies the diffraction efficiency should exceed 90% for a grating substrate treated with an anti-reflection coating. There is excellent agreement between the modelled grating efficiency and the measured data and from a least squares fit to the measured data we infer the refractive index modulation achieved during the inscription process. We also present preliminary K-band spectra of a laboratory light source obtained using one of the prototype gratings. These encouraging preliminary results demonstrate that ultrafast laser inscription of chalcogenide glass may provide a potential new and alternative technology for the manufacture of astronomical diffraction gratings for use at near-infrared and mid-infrared wavelengths.

9912-103, Session P1

Thin-film optical pass band filters based on new photo-lithographic process for CaSSIS FPA detector on Exomars TGO mission: development, integration, and test

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A new technique based on photolithographic processes of thin-film optical pass band coatings on a monolithic substrate has been applied to the filters of the Focal Plane Assembly (FPA) of the Colour and Stereo Surface Imaging System (CaSSIS) that will fly onboard of the ExoMars Trace Gas Orbiter to be launched in 2016 by ESA.

The FPA including the detector, integrated by Selex ES under TAS-I responsibility, is one of the spare components of the Simbio-Sys instrument of the Italian Space Agency (ASI) that will fly on ESA's BepiColombo mission to Mercury. The detector, developed by Raytheon Vision Systems, is a 2kx2k hybrid Si-PIN array with a 10 ?m pixel. The detector is housed within a block and has filters deposited directly on the entrance window. The window is a 1 mm thick monolithic plate of fused silica. The Filter Strip Assembly (FSA) is based on dielectric multilayer interference coatings, 4 colour bands have been selected with average in-band transmission greater than 95 percent within the CaSSIS wavelength range (400-1100 nm). This manufacturing approach gives multispectral images on the same detector and thus allows CaSSIS to operate in push-frame mode.

The Field of View (FOV) of each colour band on the detector is surrounded by a mask of low reflective chromium (LRC), which also provides with the straylight suppression required (an out-of-band transmission of less than 10^-5/nm). The mask has been shown to deal effectively with cross-talk from multiple reflections between the detector surface and the filter.

This paper shows the manufacturing and optical properties of the FSA filters and the FPA preliminary on-ground calibration results.

9912-104, Session P1

Novel diffraction gratings for next generation spectrographs with high spectral dispersion

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We are developing birefringence volume phase holographic (birefringence VPH) grating, quasi-Bragg grating and immersion grating as novel high dispersion gratings for 8.2m Subaru telescope, Thirty Meter Telescope and a next generation huge space telescope. The birefringence VPH grating uses liquid crystal of visible light curable mixed with UV curable resin. The quasi-Bragg grating is fabricated by lamination of mirror plate with emboss and UV curable adhesive. We introduce Si immersion gratings (grism) fabricated by using a diamond endmill with 60 blades.

9912-105, Session P1

Manufacturing and coating of optical components for the EnMAP hyperspectral imager

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The hyperspectral imager of the Environmental Mapping and Analysis Program (EnMAP) utilizes an optical system consisting of both mirrors and prisms in order to achieve the required imaging properties and spectral performance. The imager consists of a TMA and two independent spectrometers which measure the solar radiance reflected from the surface in a continuous spectrum.

The VNIR spectrometer contains five spherical and aspherical mirrors and four curved prisms. The ultraprecise mirrors were manufactured by diamond turning of electroless NiP plated Al6061 substrate. After polishing the surface the roughness of the mirrors was better than 1 nm rms. The applied coating was a high-reflective protected silver coating optimized for the spectral range 420 nm to 1000 nm. The reflectivity is higher than 95 % from 420 nm to 500 nm and higher than 96 % from 500 nm to 1000 nm. Two curved prisms (substrate material Fused Silica) were coated with a broadband antireflection coating optimized for small polarization sensitivity, especially in the spectral range from 600 nm to 900 nm. Two curved prisms (substrate material SF6) were coated with a broadband antireflection coating on one side and a high-reflective enhanced Ag-coating on the backside.

The SWIR spectrometer contains five plane and spherical mirrors and two curved prisms. As the mirrors for the VNIR spectrometer these ultraprecise mirrors were manufactured by diamond turning of Al6061 substrate materials coated with an electroless NiP polishing layer and have a comparable surface quality and surface shape deviation. These mirrors are coated with a gold-coating in order to achieve a reflectivity higher than 97.5 % in the spectral range 900 nm to 2450 nm. The two curved SWIR-prisms (substrate material Fused Silica) are coated with a broadband antireflection coating.

This contribution will report on the manufacturing of the mirrors and the coating of both mirrors and prisms. The most important technological steps and the achieved results will be discussed.

9912-106, Session P1

Novel fabrication methods of silicon and germanium gratings for infrared astronomy

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Single crystal silicon and germanium is an excellent optical material in the infrared astronomical spectroscopy. We developed a ductile-mode micro

grooving process for fabricating diffraction gratings made of silicon and germanium. We report a trial of the new fabrication methods of silicon and germanium gratings for an infrared astronomical instrument, Mid-Infrared Multi-field Imager for gaZing at the UnKnown Universe (MIMIZUKU). The MIMIZUKU is the first generation instrument of the University of Tokyo Atacama Observatory (TAO) 6.5-m telescope. We developed new fabrication methods of a silicon grism designed for KL-band spectroscopy in MIMIZUKU.

In the past work, we had developed a ductile mode grinding in order to fabricate immersion gratings made of germanium substrate. Although the ground surface roughness is enough good for mid-infrared spectroscopy, tip radius of grinding wheel is limited to be larger than several microns because of tool ware in grinding process. In order to overcome this situation, single crystalline diamond (SCD) cutting tools have been developed for fabrication of the grism . We adopt an ultra-precision cutting technique to fabricate micro grooves for grisms. New shaper and milling SCD cutting tools have been developed for this purpose.

A shaper SCD tool is formed into v-shape with negative rake angle to fabricate v-grooves ductilely in brittle materials like silicon and germanium crystal. A milling SCD tool has 60 cutting edges fabricated 3-dimensionally on the edge of a cylindrical SCD by a laser beam.

In the preliminary cutting experiments, the workpiece of silicon was machined using ultrahigh precision machine tools and the developed SCD tools to evaluate machinability of silicon substrate in ductile regime and its tool wear.

9912-107, Session P1

Performance characteristics of advanced volume phase holographic gratings for operation in the near infrared

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Volume phase holographic (VPH) gratings have proven useful as dispersing elements in astronomical spectrographs over the visible spectrum. VPH gratings have also been successfully deployed for use at cryogenic temperatures. Recent advances in production technology now permit the production of gratings for use in the H-band and K-band on optical materials needed for high throughput in the near infrared.

This paper discusses the limitations a common VPH grating material, dichromated gelatin, imposes on the production of near infrared grating elements as well as the practical limitations of testing.

The theoretical expectations generated by three RCWA optimized designs are presented. The H-band grating operates over the wavelengths of 1500 to 1800 nm and has a grating frequency of 290 lines/mm. The two K-band gratings operate over the wavelengths of 1950 to 2450 nm and have grating frequencies of 200 and 400 lines/mm. Measured results from production of the three grating designs are given.

9912-108, Session P1

Strategies for single-point diamond machining a large format germanium blazed immersion grating

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A large format germanium immersion grating was flycut with a single-point diamond tool on the Precision Engineering Research Lathe (PERL) at the Lawrence Livermore National Laboratory (LLNL) in November – December 2015. The grating, referred to as 002u, has an area of 59 mm x 67 mm (along-groove and cross-groove directions), line pitch of 88 line/mm, and blaze angle of 32 degree. Details on flycutting a grating with a single-point diamond tool are already reported in the literature. This paper presents new strategies for flycutting a grating, most notably pre-machining the grating substrate to produce a smooth, flat, damage-free surface into which the grooves are cut. We report on the key risks for the 002u grating, accelerated test program, trade-offs that drove decisions, and experimental results.

The 002u grating has a total groove length of 350 m which required twenty-eight contiguous days to cut. The previous largest grating produced by flycutting on PERL, based on total groove length, is a zinc-selenide grating having a total groove length of 63 m which took nine days to cut. The previous largest germanium gratings cut on PERL are grisms for LMIRcam, which have a total groove length of 7.8 m. Comparing gratings by total groove length instead of area accounts for line density and provides a comparison basis for issues like tool wear and cutting days required. By this measure, the 002u grating is five times larger than the previous largest grating (Zn-Se) cut on PERL, and forty-five times larger than the previous largest germanium grating cut on PERL. The strategies described in this paper were developed to mitigate the risks associated with the uncertainties of tool wear and keeping the PERL running for such a long grating cut, and can be applied to other gratings produced by single-point diamond machining.

The immersed grating approach, especially when using a high index of refraction substrate, provides a more compact grating diffraction geometry than is obtainable when approaching the grooves from air or vacuum. In addition the entry and exit faces of the grating substrate provide refracting surfaces for controlling optical performance. With the appropriate blaze angle, the flat-faceted, saw?tooth shaped groove profile of a blazed grating provides the highest diffraction efficiency at the wavelength of interest. The grating geometry depends on the design of the overall optical system the grating is used in, and can be optimized during trade-offs among all the optical components. Grating grooves can be produced by chemical etching – if the substrate lends itself to etching – or by single-point diamond machining. Chemical etching can produce a flat blaze face if the groove geometry is aligned to the substrate crystallographic axes. Single-point diamond machining can produce flat blaze faces even when the groove geometry is not aligned to the substrate crystallographic axes, and therefore provides increased design freedom for the overall optical system.

9912-109, Session P1

Programmable CGH on photochromic material using DMD

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Computer Generated Holograms (CGHs) are useful for wavefront shaping and complex optics testing, including aspherical and free-form optics. Today, CGHs are recorded directly with a laser or intermediates masks. We propose to use a Digital Micro-mirror Device (DMD) for writing directly the CGHs. DMD is actually studied at LAM, for generating programmable slit masks in multi-object spectrographs. It is composed of 2048x1080 individually controllable micro-mirrors, with a pitch of 13.68 μm. This is a real-time reconfigurable mask, perfect for recording CGHs. We developed a first setup dedicated to hologram recording: the DMD is enlightened with a collimated beam and illuminates the CGH plate through an Offner relay, with a magnification of 1:1. In order to follow in-situ and in real

time CGH writing, the plate is imaged through the CGH substrate on a camera. It implies that the CGH's maximum size is directly limited by the DMD's size, the size of a DMD's micro-mirror corresponding to the size of a CGH's pixel. In order to write and erase CGHs during test procedure or according to different requests, we will use a photochromic plate as a sensitive material. This material, called PUR-GD71-50-ST, is opaque at rest, and becomes transparent when it is illuminated with visible light, between 400 and 700 nm; then it can be erased by a UV flash. For our preliminary tests, we recorded up to 1000x1000 pixels CGHs with a contrast greater than 10, knowing that the material is able to reach an ultimate contrast of 1000. The optical resolution of our system being around 3 μm, each pixel written is perfectly defined. We developed a second bench, dedicated to the reconstruction of the recorded images. We can calculate, write and reconstruct 2 types of CGHs, Fresnel and Fourier holograms. In both cases, the CGH is enlightened with a collimated He-Ne laser beam. Fresnel's CGH are obtained by calculating the inverse Fresnel transform of the original image at a given focus, ranging from 50cm to 2m, so it doesn't require any additional lens to reconstruct the image. For Fourier CGH, calculated with Lee's algorithm, where the magnitude and the phase of each pixel of the inverse Fourier transform of the image is encoded into a macro-pixel (a cell of 4x4 pixels), a lens has to be inserted in the beam for getting the reconstructed image. Thanks to our writing and reconstruction set-ups, we have been able to successfully record CGHs of different types, and reconstruct them with a high fidelity, revealing the potential of this method for generating programmable/rewritable CGHs on photochromic materials.

9912-110, Session P1

Cooled optical filters for Q-band infrared astronomy (15-40 μm)

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With an evolving interest in observational astronomy across the mid- and far-infrared regions that is currently being motivated by technical advances and performance envisioned from the JWST-MIRI instrument and prospective next-generation telescopes, it is clear that improvements to the spectral and mechanical performance of optical filters to measure emission features in wavebands across the 15-40 ?m Q-band region is becoming increasingly important to provide a broader spectral wavelength coverage. This infrared region contains many signatures from astrophysical objects of which measurements are derived to determine the temperature, abundance of minerals, chemical composition, and grain size distribution from circumstellar dust and gas disks, crucial to theories on the formation of planetary systems. It is further vitally important for filters to be cooled to progressively lower temperatures to reduce noise, improve measurement sensitivity and avoid overwhelming signals originating from low energy astronomical sources by minimising the self-emission from heat sources within the instrument and telescope.

The desire to extend the range of interference filtering in order to separate and isolate wavebands in these infrared wavelengths is an area of challenging thin-film research, with goals to achieve high spectral positional accuracy, environmental durability and aging stability at cryogenic temperatures whilst maximising high transparency throughput. The major difficulties to realising this are through a balance of opposing constraints in the coating multilayer which include; accommodating large increases in the number of layers, deposition processing of high layer thicknesses, accumulation of material stress, maintaining transparency of layer materials, physical thin-film quality, and structural morphology of the condensed multilayer. The technical difficulties in achieving these demanding performance requirements has hindered characterisation of the cold and dust-filled Universe by low sensitivity and poor spatial resolution comparative to other wavelength ranges, even with the latest improvements in detector sensitivity across the infrared waveband.

Substrate and film materials exhibiting transparency across the Q-band wavelength range must utilise heavy molecular compounds with low lattice absorption properties, these include alkali-halides, thallium based mixed halides, Group II-VI compounds and Group IV elements. Many of the halide materials can possess a variety of undesired properties comprising high stress, hygroscopy, colour centres and toxicity that limit their usefulness. Deposition of cadmium-based dielectrics and lead (Pb) chalcogenide thin-films on cadmium telluride, silicon and diamond substrates, while not of outstandingly high mechanical strength have been manufactured and cooled whilst maintaining good transparency performance and durability at wavelengths across the 25-40 ?m range. Further, narrow bandpass filters for the 25 ?m region have been manufactured that exhibit temperature-invariant properties with negligible wavelength shift on cooling. The unique negative temperature coefficient (dn/dT<0) of Pb-based chalcogenide salts, in combination with the positive temperature coefficient of II-VI wideband dielectric materials enable multi-cavity bandpass filters to be designed with exclusive immunity to wavelength shifts with temperature.

In this paper we review and examine the interdependence between multilayer design, optical materials and fabrication properties of interference filters for the Q-band region, together with the rationale for the selection and characterisation of infrared materials, deposition method, spectral measurements and assessment of environmental durability.

9912-111, Session P1

Study on broadband reflective coating for astronomy

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Spectral reflectance and reflective bandwidth are the key parameters of the mirror. The astronomical mirror is usually required to have both wide bandwidth and high reflection efficiency, but actually there are some defects in the coating material of mirror. Aluminum is the most commonly used material for astronomical mirror, and its average reflection efficiency is only about 90%, which is about 8% lower than silver; silver in the visible and infrared has the highest reflection efficiency, but its reflection is rapidly dropped to zero in the ultraviolet band shorter than 400nm; gold has a high reflection efficiency only in the infrared band longer than 600nm; because of the relationship between the stress and the total thickness of the all-dielectric mirror, high reflectance is only within a certain wavelength range. We have carried out the design and experiment of the wide band reflection mirror for the astronomical requirements, and have achieved some practical results: the ultraviolet enhanced silver mirror has the lowest reflectivity of 95% in the 300nm to the infrared band; the enhanced gold mirror is designed, which has better environmental stability compared with silver; all-dielectric mirrors are designed and fabricated, and successfully used in the LAMOST telescope spectrometers, the film stress is controlled properly, and surface shape has no change.

9912-112, Session P1

A local attenuation filter for accurate photometry of near-infrared bright stars

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In recent astronomical observation in the near-infrared wavelength, it is very difficult to observe bright stars because modern infrared array detectors are too sensitive and they are easily saturated. However, it is still important to observe bright stars. There are some methods which enable us to observe bright stars, for example, defocus, ND (neutral density) filters, or reducing the effective area of primary mirror and so on. These methods can attenuate the flux of bright stars and avoid the saturation but flux of other stars seen in the same image is also attenuated. Therefore, we cannot perform the relative photometry, which is crucial for the excellent photometric accuracy.

So, I have developed a special ND filter for observing bright near-infrared stars. This filter is a 60mm diameter with a 4mm thickness, on which an attenuation (1/5000 transparency) patch with an 8mm diameter is coated. This filter is expected to be installed near the focal plane of telescope. Only the flux through this patch is attenuated and the flux through outside this patch is not attenuated at all. Therefore, we can observe the attenuated bright star together with the not attenuated field stars as the reference stars for the relative photometry.

This filter has been installed to the Nagoya University IRSF 1.4m telescope at Sutherland observatory, South African Astronomical Observatory since 2013, and the test observations were carried out with the simultaneous JHKs camera SIRIUS. When we use this filter together with SIRIUS, the completely attenuated field of view is ~60" diameter and the area outer than 200" from the center of attenuation is attenuation free.

I observed 11 bright (K~1-3 mag) standard stars listed in Carter (1990) and have obtained that the averaged attenuation rates of patch are 1/5546, 1/6486, and 1/6427 for the J, H, and Ks bands, respectively. These values correspond to 9.36, 9.53, and 9.52 mag. I also examined the uniformity of transparency by pointing the standard star for 30 positions all over the attenuated area and comparing the instrument magnitude of standard star. The scatterings (rms) of instrument magnitude are 0.014, 0.015, and 0.020 mag for the J, H, and Ks bands, respectively. These values include the instability of sky transparency and so the uniformity should be better than them. This filter has been now used for the monitoring of NIR bright stars, for example, Eta Carina.

I also prepared the local attenuation filters with an attenuation patch of 1/200000(13.25 mag) for much brighter stars, including Betelgeuse, the brightest star in the Ks band, or 1/100 (5.0 mag) for less bright stars ranging 4-8 mag. Galactic or Magellanic super novae are very bright for almost all infrared camera but we are ready for them.

9912-113, Session P1

Characterization of an integrally wound tungsten and aluminum filament for use in the MMTO 6.5m primary mirror aluminization chamber

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As part of the effort to increase the reliability of the MMT Observatory (MMTO) 6.5m Primary Mirror Coating System, the specified filament has changed from a configuration in which the aluminum charge is hand wound around a tungsten filament to a configuration in which the aluminum is integrally wound with the tungsten at the time of filament manufacture. In the MMTO configuration, this filament consists of the three strands of tungsten wire and one strand of aluminum wire. In preparation of a full system test utilizing two hundred filaments fired simultaneously, an extensive testing program was undertaken to characterize these filaments using a four filament configuration in the MMTO small coating chamber (0.5m) and then a forty filament configuration in the University of Arizona Steward Observatory coating chamber (2m). The testing using the smaller coating chambers has shown these filaments provide very consistent coatings from run to run, and with the proper heating profile, these filaments greatly reduce the chance of aluminum drips. The initial filament design was modified during the course of testing by shortening the unwound filament length to match the aluminum load required in the MMTO Coating Chamber. This change increased the aluminum deposition rates without increasing the capability of the filament power supplies (commercial DC welders). A summary of the filament power, current, resistance, and deposition rate for multiple test cases is presented.

9912-114, Session P1

Improved silver mirror coating for ground and space-based astronomy

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A highly durable, UV-enhanced, silver mirror coating has been developed by ZeCoat Corporation. The coating is highly reflective (~ 97% average and 95% minimum) from 350-nm through the long IR and is relatively unaffected by exposure to warm-humid environments on earth, as well as, space radiation exposure at GEO. This paper presents polarized-angular reflectance data, as well as, the results of humidity tests and space radiation exposure tests.

9912-252, Session P1

First results on narrow bandpass steep edge optical filters for the JST/T250 telescope instrumentation

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The Observatorio Astrofísico de Javalambre in Spain (OAJ) is a new astronomical facility located at the Sierra de Javalambre (Teruel, Spain) whose primary role will be to conduct all-sky astronomical surveys. The OAJ facility has a wide-field telescope, the JST/T250; a 2.55-m telescope with a 3º diameter field of view (FoV) designed to perform the Javalambre Physics of the Accelerating Universe Astrophysical Survey (JPAS), an innovative photometric survey of more than 8000 square degrees of northern sky using 59 filters. Among them are 54 narrow bandpass (FWHM = 14.5 nm) filters continuously populating the spectrum between 370 to 920 nm with 10.0 nm steps.

The filters will operate close to, but up-stream from the dewar window in a fast converging optical beam (F# 3.64). This optical configuration imposes challenging requirements for the J-PAS filters, some of them requiring the development of new filter design solutions.

In this publication first results on 2 narrow bandpass steep edge filters with wide suppression will be shown. All filters have a physical size of 101.7 mm x 96.5 mm and 8.0 mm thickness. The thickness of the filter assembly had to be tightly controlled (< 40 µm) since the instrument works under fast convergence and observes with a mosaic of multiple filters simultaneously. The required center wavelength (cwl) uniformity was less than ±0.2 % over the whole clear aperture. This requires to push the coating design and technology to its technological limit. In addition the demanding image quality needed a strict requirement for the transmitted wavefront (RMS) to be less than lambda/2 over the whole clear aperture at 633 nm wavelength. The cwl of the 2 bandpass filters are 460 nm and 470 nm with a maximum transmission larger than 85 % in the passband. Both filters are part of the "filter comb" with a specified overlap for T > 0.7 Tmax to get continuity. The out of band blocking required a blocking of less than Tmax*10-5 on average from 250 nm and up to 1050 nm. In addition the spectral edges have to be steep for a small transition width from 5 % to 80 %. All these requirements have to be fulfilled for an operation temperature between -20°C and + 20°C.

The manufactured filters shown in this work consist of a coated substrate and an optical filter glass in order to reach the spectral requirements. The substrate is typically coated with layer systems from a plasma assisted reactive magnetron sputter process with typically more than 100 layers and a few micrometers total thickness. This coating process results in very dense and temperature stabile coatings. The inline control of the coating process was a combination of optical transmission monitoring and time/rate monitoring. Results and measurements of two steep edge narrow bandpass will be shown. The filters have a central wavelength and

a FWHM bandwidth of cwl = 460 nm and FWHM = 14.5 nm, cwl = 470 nm and FWHM = 14.5 nm fulfilling also all other demanding requirements mentioned before.

9912-253, Session P1

Photopolymer based VPHGs: from materials to sky results

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Volume Phase Holographic Gratings (VPHGs) cover a relevant position as transmission dispersing elements in astronomical spectrographs with low and medium resolution. This is due to the unique properties especially in terms of diffraction efficiency.

These devices have to provide the dispersion, resolving power, bandwidth and diffraction efficiency according to the different astronomical scientific cases and sky targets to address. Indeed, each astronomical observation could take advantage of specific dispersive elements with features tailored for achieving the best performances.

The design and manufacturing of high efficiency and reliable VPHGs require photosensitive materials where it is possible to finely control the refractive index modulation, which is, together with the film thickness, the key property that determines the efficiency.

Photopolymers are a promising class of holographic materials since they can address precisely the refractive index modulation; moreover, they are self-developing, meaning that no chemical process is required after the light exposure.

We studied a specific family of photopolymers, Bayfol® HX by Covestro AG, which show a large tuning capabilities with a good transparency over the visible and NIR spectral range and a large refractive index modulation.

Based on such good properties of Bayfol® HX, we designed and manufactured six dispersing elements for astronomical instrumentation. Starting from the astronomical requirements, the features of the VPHGs have been determined, then the optimization of the writing conditions were carried out to achieve the desired refractive index modulation.

The six VPHGs were used in a GRISM configuration. Both the prism design and GRISM assembly was performed. Three GRISMs were integrated on ALFOSC (The Andalucia Faint Object Spectrograph and Camera) mounted on the Nordic Optical Telescope (2.56 meters, La Palma, Spain) and the other three on AFOSC (Asiago Faint Object Spectrograph and Camera) mounted onto Asiago's telescope in Italy.

The three elements for ALFOSC are characterized by a resolving power of approximately 1000 and they cover the 350-1000 nm spectral range.

The three elements for AFOSC have low dispersion covering the 350-1000 nm range. Interestingly, one GRISM shows a novel architecture based on slanted fringes VPHG and just one prism, with advantages such as less production costs and optical interfaces, that may form ghosts and decrease the overall efficiency.

All the six dispersing elements matched the astronomical requirements and overcome the performances of the already mounted devices with a system throughput gain that, in some cases, surpassed the 80%.

We demonstrated how the Bayfol® HX photopolymers are reliable for making VPHGs to be used in astronomical instrumentation and we defined a working range where the performances are similar or even better than those provided by DCG based VPHGs.

9912-271, Session P1

Ultra-narrow line VIS/NIR optical filters based on holographic volume Bragg gratings in PTR glass

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High-efficiency holographic volume Bragg gratings (VBGs) provide unmatched optical filtering capabilities with diffraction efficiencies as high as 99.999% and spectral linewidth as narrow as 15 pm (or <10 GHz). That enables splitting of individual optical bands spaced less than 100 pm apart and/or suppression of unwanted signals by 5-6 orders of magnitude. These holographic optical elements are formed in a photo-thermo-refractive (PTR) glass, the material that allows recording of phase Bragg gratings with high efficiency for visible and near IR spectral regions (350-2800 nm). The refractive index modulation in PTR glass is achieved by controlled precipitation of nano-crystalline phase in the whole volume of PTR glass exposed to UV radiation. Once recorded and developed, VBGs cannot be erased by illuminating to optical and ionizing radiation or by heating unless the temperature exceeds 400oC. Unlimited life time of PTR-VBG based filters combined with unique linewidth and suppression properties greatly benefit their usage for laser systems, spectroscopy, single photon counting, hyperspectral and Raman imaging, etc. In this work we present recent advances in the VBG technologies that led to development of next generation of Bragg notch and bandpass filters with enhanced transmittance and higher optical density.

9912-115, Session P2

Transmission and opto-mechanical performance of the liquid lens coupling in the Robert Stobie spectrograph

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Fluid coupling provides good transmission efficiency over a wide bandwidth and in theory will outperform traditional multilayer coatings. However, the long term stability and reliability of the fluid coupling is very difficult to achieve in practise. This is due to chemical compatibility problems between the coupling liquids and plastics and elastomers used in the opto-mechanical design which caused degradation of the transmission of the liquid as constituent is leached out of the plastics as well as absorption of the coupling fluid by the elastomers causing swelling and compromising the opto-mechanical performance.

A recent service of the Robert Stobie Spectrograph (RSS) on SALT afforded the opportunity to inspect the performance of the liquid coupled groups within the spectrograph collimator, 6 years after assembly. The opto-mechanical design of RSS utilises Dow Corning Sylgard 184 to retain the lenses and seal in the coupling fluid. Two different coupling fluids are used in the different optical groups namely Laser Liquid 3421 and Index Matching Fluid 5610 both produced by the Cargille company.

During the service we disassembled the collimator into its main groups and measured the transmission through the groups in order to compare the transmission performance of the different coupling fluids. We also took the opportunity to measure the reflectivity of some of the coated lens surfaces which has to operate over a very wide band between 320 nm to 1750 nm. We also took transmission performance data for fluid removed from the optical assemblies.

In this paper we provide an overview of the materials exposed to coupling fluid in the RSS optical train, give a description of the experimental set-up and equipment used to measure the transmission performance utilising photometry. We report briefly on the difficulties of using Czerny–Turner monochromators as light sources causing red contamination in the blue part of the test spectrum.

We present results from transmission tests done on, the assembled groups, coupling fluid removed from the spectrograph and virgin fluid samples. We also present reflectivity test results taken from the coated surfaces. These results indicate performance degradation of the coatings to be similar in magnitude to absorption losses in the coupling fluids.

We further present laboratory data and analysis of the swelling effect of the coupling fluids on the Sylgard 184 elastomer and compare it to the performance in the spectrograph. Sylgard swells more when exposed to 5610 than with 3421, with 5610 causing swelling by 25% compared to 5% - 8% for 3421.

Finally, we summarise the lessons learned from the Instrument service and the test results, with analysis and comment on the features of the opto-mechanical design. We also provide some design guidelines for liquid coupling, including bezel design and equipment for fluid handling and filling.

9912-116, Session P2

Large optical glass blanks for the ELT generation

Ralf Jedamzik, Uwe Petzold, Olga Rexius, Volker Dietrich, SCHOTT AG (Germany)

The upcoming extremely large telescope projects like the E-ELT, TMT or GMT telescopes require not only large or large amount of mirror blank substrates but have also sophisticated instrument setups. On common instrument components are atmospheric dispersion correctors that compensate for the varying atmospheric path length depending on the telescope inclination angle. These elements consists usually of optical glass blanks that have to be large due to the increased size of the focal beam of the extremely large telescopes.

SCHOTT has a long experience in producing and delivering large optical glass blanks for astronomical applications up to 1 m and in homogeneity grades up to H3 quality in the past.

The most common optical glass available in large formats is N-BK7. But other glass types like F2 or LLF1 can also be produced in formats up to 1 m. The extremely large telescope projects partly demand atmospheric dispersion components even in sizes beyond 1m up to a range of 1.5 m diameter. The production of such large homogeneous optical glass banks require tight control of all process steps.

To cover this demand in the future SCHOTT initiated a research project to improve the large optical blank production process steps from melting to annealing and measurement. Large optical glass blanks are measured in several sub-apertures that cover the total clear aperture of the application. With SCHOTT's new stitching software it is now possible to combine individual sub-aperture measurements to a total homogeneity map of the blank. In this presentation first results will be demonstrated.

9912-117, Session P2

ULE design considerations for a 3m class light weighted mirror blank for EELT M5

Andrew Fox, Mary J. Edwards, Thomas W. Hobbs, Corning Incorporated (United States)

It is expected that the next generation of large ground based astronomical telescopes will have a need for large fast-steering / tip-tilt mirrors, made of ultra-lightweight construction. These fast-steering mirrors are used to continuously correct for atmospheric disturbances and telescope vibrations. An example of this is the EELT M5 lightweight mirror, which is part of the Tip-Tilt / Field-Stabilization Unit. The EELT Tip-Tilt Unit will be used to correct for low bandwidth tip-tilt errors arising from the effects of the wind on the telescope and larger amplitude errors from the atmosphere.

Corning has a long history of manufacturing lightweight mirror blanks using Corning ULE® in a closed-back construction. Corning's closed-back lightweight ULE® history goes back to the 1960's and includes the Hubble Space Telescope primary mirror, Subaru secondary and tertiary mirrors, Magellan tertiary mirror, and Kepler Space Telescope primary mirror, among many others. Corning can achieve lightweighting using abrasive waterjet (AWJ) cutting and CNC machining. These technologies can be leveraged for mirror design flexibility, enabling the manufacture of custom core structures to achieve an ideal design of light weight and high stiffness. Corning's capability to seal a continuous back plate to the core structure provides mirror rigidity, in a zero thermal expansion material, that meets or exceeds any other existing technology used in this space.

The baseline design for the EELT M5 mirror, as presented in the E-ELT Construction Proposal, is a closed-back ULE® mirror with a lightweight core using square core cells. This design provided exceptional mirror performance; with an aerial density below 70 kg/m2 and a first eigenfrequency above 290 Hz. Corning has investigated the performance of other lightweight designs leveraging elements of Corning's current manufacturing capabilities. Various mirror blank parameters were adjusted for different scenarios, including: mirror thickness, back face sheet shape, rib thickness, face sheet thickness, percentage of back face sheet coverage, core cell patterns (including triangular, hexagonal, and square), and core cell size. Finite Element Analysis was performed on the design scenarios to obtain: Weight, Aerial Density, First Eigenfrequency, and Gravity deformation at load cases pertinent to the EELT M5. In this paper, the performance of each design scenario will be reviewed and discussed, as well as the manufacturing advantages and disadvantages of each scenario.

9912-118, Session P2

High volume ULE segment production

Andrew Fox, Mary J. Edwards, Thomas W. Hobbs, Corning Incorporated (United States)

It is expected that many of the next generation of large ground based telescopes will utilize a segmented design for the primary mirror and, in some cases, the secondary mirror. The segmented mirrors are made of many hexagonal segments, each approximately 1.4 to 1.8 meters in size, and positioned in an array to emulate the parent optic. Many 10 meter class telescopes currently in operation utilize a segmented primary mirror, such as: Keck I and II, GTC – Gran Telescopio CANARIAS, HET – Hobby-Eberly Telescope, and SALT – South African Large Telescope. The number of mirror segments in these telescopes range from 36 to 91, based on the segment size. Next generation extremely large telescopes (ELTs) will contain many more segments. The Thirty Meter Telescope and European Extremely Large Telescope will contain 492 and 798 segments respectively. As the number of mirror segments increase, cost, capacity, and production speed of the mirror segment blank manufacture become increasingly critical. Corning has the capacity and capability to produce mirror segment blanks from Corning ULE® titania-silica glass in various segment sizes. Corning also has the ability to produce large monolithic mirrors for use in secondary, tertiary and other mirror blanks up to 4 meters in diameter.

Corning ULE® is manufactured in what is known as "boules." Typical boules are approximately 1.5 meters in diameter and 150 mm thick. The boules are fully characterized for room temperature coefficient of thermal expansion (CTE) using a non-destructive ultrasonic technique, which can be done without taking sacrificial samples. Segment manufacturing consists of cutting the boule into a hexagonal shape (a "hex"), slicing the hex with a gang wire saw to near net thickness, followed by final CNC grinding of the surfaces to achieve final specifications. Corning uses the same process to generate hexes that can be fused together to create large monolithic mirror blanks. Hundreds of these hexagonal segments have been produced by Corning in recent years for various projects. Thus, the fixed assets, resources, and expertise are established and remain in place to produce segments for future projects.

This paper will describe the facilities, equipment, resources, and processes employed by Corning to produce several hundred to several thousand mirror segment blanks, as well as large monolithic mirror blanks, for extremely large telescopes. Corning's manufacturing capacity will also be discussed. In 2006, a paper was published entitled "Review of Corning's Capabilities for ULE® Mirror Blank Manufacturing for an Extremely Large Telescope." Since 2006, as ELT programs have evolved, Corning's ULE® capacity and blank manufacturing capabilities have also evolved. This paper is intended to review and update the information and details previously presented.

9912-120, Session P2

Smart telescope for astronomy

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In this paper, we present the preliminary design of a smart telescope, i.e. an optomechanical device whose structure is able to monitor external loads (gravity, wind, thermal gradients, displacements caused by earthquake) and actively adapt to them in order to correct misalignments. To obtain that, the proposed solution foresees the use of smart materials, or rather integrated smart structures containing sensors (such as fibre optics), and actuators (shape memory alloys or piezoelectric). Starting from the optical design, where the primary mirror is supposed to be in the class of 60cm diameter, with this work we illustrate the mechanical design philosophy. The basic idea is to conceive of a "low-performance" telescope from the stability point of view, in order to emphasize the environmental loads contributions, show that it is possible to correct them a posteriori, and generalize the results for more optimized structures (Serrurier-like). Therefore, it is shown the finite element model of a first naked version of the telescope (without smart structures), useful to know the displacements caused by predictable loads. Then, we describe the host material selection and the embedding technology of the smart materials, followed by the integrated modeling, to finally get the telescope upgrade.

9912-121, Session P2

Advanced structural design for precision radial velocity instruments

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The GMT-Consortium Large Earth Finder (G-CLEF) is a fiber fed, optical echelle spectrograph that has been selected as a first light instrument for the Giant Magellan Telescope (GMT) being constructed at the Las Campanas Observatory in Chile's Atacama Desert region. G-CLEF has been designed to be a general-purpose echelle spectrograph with precision radial velocity (PRV) capability used for exoplanet detection. The radial velocity (RV) precision goal of G-CLEF is 10 cm/sec, which will enable it to detect Earth-like exoplanets in the habitable zones of sun-like stars. This goal imposes challenging stability requirements on the instrument's optical bench structure, optical mounts, and spectrograph support structures. Stability of the instrument and PRV accuracy will be affected by changes in temperature, air pressure, orientation relative to gravity, and vibrations caused by telescope movement. Extremely small image motions at the red and blue CCD detectors can degrade RV precision. Extreme stability requirements are required to minimize image motion. These requirements drove the selection of a carbon fiber/cyanate monocoque design for the primary optical bench structure to ensure that 10 cm/s PRV capability is maintained under the range of observational environments. Low CTE and high stiffness-to-weight are key features of the composite optical bench design. Manufacturability and serviceability of the instrument are also drivers of the structural bench design.

Maximum expected environmental loads during an observation include:

• Milli-Kelvin (0.001 °C) thermal soaks and gradients

• 10 m-bar ambient pressure change applied to the vacuum vessel which print through to the bench via quasi-kinematic flexure supports

• Changing gravity vector at instrument during slewing due to 116 ?-radian GMT azimuth axis misalignment with gravity over 360° azimuth, local azimuth track height variability, and flexure of the azimuth platform.

In this paper, we discuss the design of G-CLEF's optical bench and support structures including technical choices made to minimize the system's sensitivity to changing thermal gradients, acceleration environments, and print-through of atmospheric pressure variations into optical bench flexure mounts. The results of Finite Element Analysis (FEA) and sensitivity studies indicate the PRV performance ramifications of a variety of bench materials including mild steel, stainless steel, Invar-36, and carbon fiber composite. We discuss the design of the optical bench structure to optimize stiffness-to-weight and minimize deformations due to inertial effects. We also consider fiber and matrix materials options to ensure near-zero CTE, low moisture uptake, minimized CME effects, and minimal outgassing. Design of titanium mounting flexures for stable quasi-kinematic support of the instrument is discussed. We also discuss quasi-kinematic mounting of optical elements and assemblies, and optimization of these to ensure minimal image motion under thermal, pressure, and inertial loads expected during PRV observations.

9912-122, Session P2

Complex structures with extreme stability requirements for opto-mechanical applications

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During a current project under OHB, Germany contract ECM is designing, fabricating and testing an extreme stable structure to demonstrate that HB-Cesic® properties at various temperatures are fully appropriate to the manufacturing of complex highly stable optical structures.

ECM together with its industrial partners designed, manufactured and tested several complex light weighted structures of its proprietary ceramic material "HB-Cesic ". The opto-mechanical structures have fulfilled extreme stability requirements under typical non stabilized space Environment. In this paper we report about fabrication, integration and testing of a recent example of such extremely thermal stable structure.

9912-123, Session P2

ESPRESSO optical bench: from mind to reality

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ESPRESSO is a high-resolution spectrograph under development for the VLT telescope. One challenge of the instrument opto-mechanical design is

to obtain the highest dimensional stability.

The Optical Bench allows the opto-mechanical mounts, and therefore the optical elements, to be supported and placed relatively among them, tracing out in an approximate way the optical layout. The design of an optical bench in order to optimize dimensional stability is indeed conditioned by selected materials and manufacturing process especially if the target is to keep dimensional stability about 1 ?m or even lower. At this level of accuracy all material properties and manufacturing process must be considered in order to assess their influence over the optical bench and optimize the design of structure in order to minimize their influence upon dimensional instability. In general, the OB structure can be considered as a 3D one, conformed by welding thin plates of Structural Steel (St-52) with a nickel-plated surface treatment, combined for getting maximum stiffness and minimum weight, that will be finally re-machined to get stringent geometrical and dimensional tolerances at I/Fs positions. TIG conventional welding procedure have been selected to minimize the cost and facilitate the own welding process. This solution follows the inheritance from HARPS due to its success to achieve the required performance for the bench.

Key features and performances:

• Upper and Lower base plates, and longitudinal and transverse lower stiffeners with a thickness of 20 mm

• Upper and lower side plates, and interface plates with the cameras with a thickness of 15 mm

• Rest of stiffeners with a thickness of 12 mm

• 3 support points, one in the lower part of the collimator mirror, and two in the joining of the upper base plate and the side stiffeners

• Enough stiffeners, including internal ones

• Enough pockets to facilitate the accessibility to the subsystems

• Overall dimensions: 3400x1400x1450 mm

• Approximate weight: 2970 Kg

• Maximum deformation: 65,3 microns

• Maximum Von-Misses stress: 34,5 MPa

• First Eigen-frequency: 91,1 Hz

This poster contains an overview of the whole process of designing and manufacturing the Optical Bench of ESPRESSO, from the very first beginning with the specifications to the current status of the bench with its integration on the Spectrograph (including the Finite Element Models and the delivery of the final structure by the supplier).

Some remarks are done, mainly in the manufacturing process to assure the stringent stability performances.

9912-124, Session P3

Approaching perfection in the manufacturing of silicon immersion gratings

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Silicon immersion gratings make near-IR spectrographs compact and allow them to have continuous wavelength coverage over a large bandwidth. We have produced a silicon immersion grating (hereafter ES2) that is, for all intents and purposes, optically perfect. An optimally flat immersion grating operating at the diffraction limit has peak-to-valley (PV) surface error of less than ?/4 where ? is the operating wavelength in immersion. Silicon is opaque to wavelengths shorter than 1.15?m, so a grating that is optically perfect down to this limiting wavelength will have a PV surface error of less than 85nm. ES2 approaches this ideal limit and has a PV surface error of 102nm over a 25mm beam.

Achieving this level of precision is difficult given that large-scale and periodic errors can be introduced in a number of the silicon processing steps. Our ability to reduce large-scale imperfections is essential for instruments operating near the diffraction limit. However, when the slit is significantly wider than the diffraction limit, large-scale errors will affect neither resolving power nor efficiency. We produce silicon immersion gratings using a contact printing method in which we coat the polished surface of a cut of silicon with a passivation layer (silicon nitride) and subsequently a UV-sensitive photoresist layer. We then pattern lines onto the surface using contact photolithography, etch the passivation layer in a reactive ion etch process and then etch grooves into the silicon substrate in a potassium hydroxide solution. We have linked the introduction of large-scale errors to non-uniformity in the illumination of the substrate by the UV exposure system during the patterning step. In order to reduce the level of these errors we have honed our contact printing method by optimizing our UV exposure system, introducing additional process checks and inspections and carefully evaluating large-scale and periodic errors in the gratings produced. These improvements to our standard process have allowed us to consistently produce instrument quality gratings including ES2, which will be used for the K-band channel of the Giant Magellan Telescope Near Infrared Spectrograph (GMTNIRS). Silicon immersion gratings will allow GMTNIRS to achieve continuous wavelength coverage over the J, H, K, L and M photometric bands in a single exposure. With their ability to produce spectral formats that permit continuous wavelength coverage, their high efficiency, and with the compactness that they enable, immersion gratings are now the dispersive devices of choice for high-resolution spectroscopy in the near-IR.

9912-125, Session P3

Towards freeform curved blazed gratings using diamond machining

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Concave blazed gratings greatly simplify the architecture of spectrographs by reducing the number of optical components. The production of these gratings using diamond-machining offers practically no limits in the design of the grating substrate shape, with the possibility of making large sag freeform surfaces unlike the alternative and traditional method of election beam lithography. In this paper, we report on the technological challenges and progress in the making of these curved blazed gratings using an ultra-high precision 5 axes Moore-Nanotech machine. The goal is to develop the technologies for the production of the next generation of low-cost, compact, high performance spectrometers.

9912-126, Session P3

Nonconventional ultra-precision manufacturing of ULE mirror surfaces using atmospheric reactive plasma jets

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Most designs of next generation of extremely large astronomical telescopes (ELTs) employ segmented primary mirrors. These are made up of hexagonal segments a bit larger than 1 meter in size, each manufactured with appropriate optical figure for their position in an array emulating the parent optic. Extremely large future telescopes each need of order 1000 segments that constitute a significant challenge in cost and schedule. The projects working to construct these telescopes have chosen approaches such as direct fabrication and warped segment polishing in pursuit of the lowest cost, highest fabrication rates, and acceptable optical figure. Since optical figuring is usually disproportionately expensive and time consuming, an alternate process is proposed to demonstrate

the manufacture of segments more rapidly and at lower cost via these approaches than those which constitute the current baseline for the ELTs under development. IOM has developed a process for Plasma Jet Machining (PJM) of optical surfaces. PJM is based on an atmospheric chemically reactive plasma jet tool that locally interacts with the optical surface in order to remove material by chemical reactions forming volatile species. Corning's proprietary near zero CTE material, ULE®, has been proven particularly suited to be processed by PJM. The process has been shown to achieve high material removal rates up to 50 mm?/min, that can be leveraged to shorten the time required to attain the desired optical figure. The plasma jet tool exhibits special features from its working principles such as sub-surface damage free material removal or insensitivity to machine vibration. Furthermore, the tool function is nearly independent on local radius of curvature thus being appropriate for freeform generation or error structure correction. The tool width (typically the full width at half maximum of a Gaussian function) can be scaled down to 1mm to address mid-spatial frequency surface structures. A proof-of-principle experiment has been performed on ULE® roundels of 200mm diameter and 30mm center thickness with a 650mm ROC concave spherical surface supplied by Corning that have been conventionally ground and polished. Spherical shape has been chosen to simplify testing.

Two different tool function widths have been consecutively applied in the dwell-time based figuring process achieving residual form errors of 5 nm RMS.

The paper summarizes the optimization of the PJM process to be effective on ULE® and providing high efficiency and reproducibility. It discusses the results of form error corrections and shows the potentials of PJM for fast fabrication of large optical surfaces.

9912-127, Session P3

Vibrating mirror concept for adaptive optics

Mousa Hadipour, Murat Tahtali, Andrew J. Lambert, The Univ. of New South Wales (Australia)

A new Vibrating Membrane Mirror (VMM) based on the vibration modes of membranes is proposed as a simple and inexpensive alternative to the traditional adaptive optics mirrors to mitigate wavefront aberrations. Elimination of the large number of complex micro-actuators present in traditional Deformable Mirrors (DM) used to control the reflective surface is the main advantage of this proposed VMM. It leads to a simpler control system, lower weight, higher control speed, lower fitting error, and lower overall manufacturing cost. It is suitable for systems where pulsed light or strobed exposure can be synchronized to the desired phase and excursion of the membrane.

Zernike Circular polynomials (ZCP) are used traditionally to approximate the aberrations caused by atmospheric turbulence. Using the orthogonality property of these polynomials it is possible to combine many different ZCP on a surface, and combine numerous surfaces, as needed to express the shape of arbitrary wavefront deviation with desired fitting accuracy. Bessel polynomials, which form the solution for the partial differential equation of motion of a vibrating membrane, and hence describe the vibrational modeshapes of circular membranes under tension, are orthogonal functions with similarity to ZCP. The general behavior of a vibrating membrane can be expressed using the principle of superposition of modeshapes. These similarities are exploited to find the degree of resemblance between the modeshapes of vibrating membrane and the surface changes of a DM to compensate for wavefront aberrations.

In this study, which follows from [1], first a finite element model of a piezoelectric PVDF (PolyVinylidene Fluoride) circular membrane is developed and its dynamic characteristics extracted. Its natural frequencies are compared with its analytical solution. The extracted modeshapes are compared with the ZCP to determine the corresponding modeshapes that bear the highest resemblance to the main wavefront aberrations. The similarities between the radial function of ZCP and the first kind Bessel functions are investigated and the degree of similarity is quantified using the root mean square error (RMSE) metric. Results show that the mean RMSE values between normalized modeshapes and the corresponding Zernike descriptions of seven common aberrations were below 0.2. An optimum diameter and a scaling factor for each modeshape are obtained to minimize this metric, and which form the effective aperture. As the vicinity of the excitation may become the site of undesired vibrations, the idea of using higher order modeshapes is proposed, and an excitation area, called the excitation ring is introduced. To achieve this, the excitation frequency is increased to create an extra circular node in modeshapes, while the desired modes are maintained within the effective aperture. A transient dynamic finite element analysis is performed to track the mode transitions and to compare them to previous experimental results [1], for which good agreement is observed.

In summary, the possibility of using vibrating membrane mirrors instead of the expensive traditional DM is investigated using numerical and analytical analysis. Fundamental concepts are discussed and practical solutions to avoid problems in empirical experiments are proposed. Future work will entail the experimental implementation of these concepts.

[1] Tahtali M and et al., Using the Modeshapes of a Vibrating PVDF Film as a Deformable Mirror Surface, in CANEUS. 2006, ASME DC: Toulouse, France. p. 31-36.

9912-128, Session P3

A segmented subreflector with electroformed Nickel laminated panels for the Large Millimeter Telescope

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The Large Millimeter Telescope (LMT) Alfonso Serrano is a 50 m diameter single-dish radio telescope optimized for astronomical observations at wavelengths of about a millimeter. Built and operated by the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE) in collaboration with the University of Massachusetts (UMASS), the telescope is located at the 4600 m summit of volcano Sierra Negra, Mexico. The principal scientific goal of the telescope is the investigation of the physical processes underlying cosmic structure formation and its evolutionary history throughout the Universe.

Anticipating the completion of the 50 m main reflector, currently operating over a 32 m sub-aperture and expected to be aligned to an overall residual surface shape error of less than 50 μm RMS, INAOE has also scheduled the replacement of the 2.6 m monolithic Aluminum subreflector with a new higher-precision unit that will enable higher efficiency astronomical observations with the entire main reflector surface. In this project, INAOE has contracted Media Lario for the design and manufacturing of the subreflector, continuing a consolidated collaboration started in 2004 for the supply of the Nickel laminated panels for the main reflector.

The new 2.6 m M2 subreflector is segmented in 9 smaller reflector panels, one 1.2 m central dome and eight identical petals, assembled and precisely aligned on a steel truss structure that will be connected to the tetrapod head via a hexapod (supplied from separate contract). Each reflector panel is fabricated with Media Lario's unique laminated technology consisting of front and backside Nickel skins, produced by electroforming replication from a precise mold, that are bonded to a lightweight Aluminum core. The result is an extremely light and rigid laminated panel with a shape precision better than 7.5 μm RMS, expecting a total operational shape accuracy performance better than 20 μm RMS over the 2.6 m subreflector, which is well within the telescope error budget. The reflecting surface of each panel is given a thin galvanic Rhodium coating that ensures that the reflector survives the harsh environmental conditions at the summit of Sierra Negra without the need of any specific maintenance during the 30 year lifetime of the telescope. The segmented design carries the additional benefit that in the event of accidental damage, individual panels can be replaced and realigned separately, achieving a significant cost saving with respect to the current design. The total mass of the subreflector is about 210 kg, well within the 280 kg requirement set by INAOE.

After having completed the final design review in October 2015, Media Lario is now into the manufacturing tasks, and approaching completion of integration, assembly, and qualification of the subreflector. In this work, we will explain the design approach, illustrate the simulated operational performance in relevant astronomical observation conditions, report the shape measurements of the reflector segments and truss structure, describe the metrology and integration procedure implemented to reach the 20 μm RMS target for the entire subreflector surface, and finally report the qualification results on the fully assembled and aligned 2.6 m subreflector.

9912-129, Session P3

Optimisation of grolishing freeform surfaces with rigid and semi-rigid tools

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With success at the National Facility for Ultra Precision Surfaces in completing formal acceptance of prototype mirror-segments for the E-ELT, we are investigating further solutions to improve process steps that can accelerate segment mass production. Developments based on Zeeko's Precession technology have been proven to be effective for meeting form, mid-spatial, edge and texture specifications. However, an intermediate smoothing/grolishing will be highly beneficial to remove mid-spatial features before segments reach the polishing stage. To save valuable machine time on the CNC polishers, we aim to deliver the grolishing tasks on lower-cost industrial robots.

We have previously reported on areas such as tool design and toolpath generation, implemented on both Fanuc and ABB robots in our Facility. However, all of that work was conducted on flat or spherical parts. In this paper, we present new results evaluating the processes on aspheres for the first time, and in particular, report on studies of the effects of mismatch between a rotating tool and a work-piece for different abrasive types. In order to progress this, we have developed a bending rig which is capable of bending a flat glass sample to varied cylindrical radii of curvature. We report on the effectiveness of this test setup, and then present results for different combinations of aspheric mis-fit, bound or loose abrasive grit size, and type of tool-path used. We also explore flexible tooling including Non-Newtonian tools.

9912-130, Session P3

Polarization properties of ultra-fast laser inscribed waveguide array

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Recent development of ultra-fast laser inscription technology for the fabrication of waveguides offers a new possibility for astronomical spectroscopy to bypass many undesirable properties and limitations intrinsic to conventional optical fibers. The ability of ultra-fast laser inscription to construct complex distribution of waveguides in three dimension further provide a new integral field units (IFUs) fabrication method that allows us to build very large format high performance IFUs free of modal noise associated with fiber-optic IFUs. Without bending induced stress birefringence, these new photonics IFUs may also have important benefits for the field of astronomical spectropolarimetry. In this paper we will present measurements of polarization maintenance and in-waveguide polarization crosstalk of a 121-waveguide fan-out device that reformats a 2D spatial field into a 1D linear array for coupling into diffraction grating spectrograph. These measurements will be used to examine how polarized waves propagate through ultra-fast laser inscribed waveguides for evaluation of their suitability for astronomical spectropolarimetric applications.

9912-131, Session P3

Manufacturing of a new aluminium back-up secondary mirror for SOFIA

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The Stratospheric Observatory for Infrared Astronomy - SOFIA - is an air-borne observatory designed to operate at wavelengths from 0.3 ?m to 1.6 mm. The 2.5-m effective diameter telescope has been built to cover this entire range. The telescope itself is a Cassegrain design with a convex, hyperbolic secondary mirror (M2). To enable efficient chopping, which is needed to suppress variable sky-noise via synchronous demodulation of signals from astronomical sources, the secondary mirror needs to be light in weight and low in inertia.

The M2, having a diameter of 352 mm, was made from silicon carbide and weighs only 1.9 kg. As this material is brittle, and the secondary mirror is indispensable to observations with SOFIA, a back-up mirror with the same mass and moments of inertia is required.

A first back-up mirror was made of Al 6061 aluminium in 2004. This mirror, however, allows diffraction-limited observations only above 20 μm and it produces double peaked images as seen in ground-based measurements using this mirror in 2004. In 2012, the work on a new, improved Aluminium backup secondary mirror began.

At first RSA6061 has been selected as base material for the mirror. This material is chemical identical to regular Al6061. However, a specific, rapid solidification process is used to produce the raw material. This material has a much more refined structure, enabling a lower surface roughness after the Single Point Diamond Turning Process (SPDT), typical Rq values of 1 to 2 nm RMS compared to 10 to 15 nm RMS in regular 6061.

A dedicated interface was designed to obtain a stress-free mounting of the mirror during SPDT-processing. Despite all these precautions it turned out that the mirror did deform unacceptable after dismounting from the interface. An in depth analysis pointed towards internal material stresses introduced during the quenching step of the heat treatment of the material.

After a re-evaluation of potential mirror materials RSA 905 was selected. The manufacturing was executed according to planning and the mirror has been delivered to the Deutsches SOFIA Institute. The final mirror has a surface roughness Rq <3.5 nm RMS a form-error of 121 nm RMS over the full aperture and a PV-error of 700 nm. This is an approximately 10 times lower form error and a 7 times lower surface roughness, compared to the first Aluminium mirror from 2004. In the paper details on the material selection and final results will be discussed.

9912-132, Session P3

Manufacturing methods of testing the large-size optics at the stage of grinding, aspherical surface centering, and positioning the interface elements before gluing

Aleksandr P. Semenov, Lytkarino Optical Glass Factory JSC (Russian Federation); Magomed A. Abdulkadyrov, JSC Lytkarino Optical Glass Factory (Russian Federation); Vladimir E. Patrikeev, Lytkarino Optical Glass Factory JSC (Russian Federation)

Technology with the use of programmable computer-controlled system and a set of special instruments, which makes possible aspherization of off-axis large-size optical elements of astronomical and space telescopes with deviation from the nearest sphere of more than 1 mm, was developed.

9912-133, Session P3

Studying the stability of Astrositall thermal and mechanical properties while manufacturing the astronomical and space mirrors

Aleksandr P. Semenov, Magomed A. Abdulkadyrov, Alexey P. Patrikeev, Sergey P. Belousov, Aleksandr N. Ignatov, Vladimir E. Patrikeev, JSC Lytkarino Optical Glass Factory (Russian Federation)

The technology of producing the astronomical and space mirrors from Astrositall? material, including its properties and stability of these properties in the course of time, is described. The results of long-term material tests are presented. In particular, the method of grinding and polishing the off-axis segment of the mirror of very large telescope in the stress-strain state is considered.

9912-134, Session P3

Diamond fly cutting of aluminum thermal infrared flat mirrors for the OSIRIS-REx Thermal Emission Spectrometer (OTES) instrument

Christopher E. Groppi, Matthew Underhill, Zoltan Farkas, Arizona State Univ. (United States)

We present the fabrication and measurement of monolithic aluminum flat mirrors designed to operate in the thermal infrared for the OSIRIS-Rex Thermal Emission Spectrometer (OTES) space instrument. The mirrors were cut using a conventional fly cutter with a large radius diamond cutting tool on a high precision Kern Evo 3-axis CNC milling machine. The milling machine's cutting spindle thermal growth compensation system was disabled, and the cooling fluid loop re-routed through a flat plate heat exchanger cooled with a process chilled water system rather than the machine's internal spindle cooling fluid chiller. This reduced the amplitude of disturbances in the finished flat mirror from ~0.5 micron down to less than 150 angstroms RMS. This represents a novel use of a conventional (albeit very high precision) conventional milling machine to diamond cut flat mirrors rather than use a specialized optical diamond turning machine. The ~20mm diameter flat mirrors were cut with a single pass of the diamond fly cutter, then measured with an optical laser interferometer. The full complement of flight mirrors and spares, along with test articles were cut with this technique. The delivered components were accepted by the OTES team and will fly on the instrument when launched in 2016.

9912-135, Session P3

Combined fabrication technique for high-precision aspheric optical windows

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Specifications of optical components are becoming more and more stringent with the performance improvement of modern optical systems. These strict requirements not only involve the low spatial frequency surface accuracy, but also the mid-and-high spatial frequency surface errors, surface smoothness and so on. Nowadays, deterministic figuring technologies are developed to meet the growing demands of such high-precision optical components. This munuscript will report the fabrication process of a square aspheric optical window in our laboratory, which combines accurate grinding, magnetorheological finishing (MRF) and smoothing polishing (SP). We will highlight the applications for full spatial frequency errors control in different stages based on their inherent capability.

Accurate grinding can form the shape of optics quickly. However, series of issues would exist after grinding of high precision surfaces, such as the limit of accuracy, defects on subsurface and marks on surface. Fortunately, MRF is a deterministic polishing method with high convergence and high removal rates. It is an advanced technology which can remove the low spatial frequency surface errors and subsurface defects effectively. SP also exhibits excellent performance in eliminating mid-and-high spatial frequency surface ripples and high slope errors. Consequently, the combined fabrication technique is developed to fabricate the high-precision optical windows with high efficiency. Additionally, exact measurements are also vitally important for the high-performance optical component. The effective association of coordinate measuring method and interferometer metrology in the process are both investigated. The experiment validates the high-efficiency of this combined fabrication technique for high-precision optical windows.

9912-136, Session P3

Process optimization of laser-based solderjet bumping for mounting of optical components

Thomas Burkhardt, Marcel Hornaff, Andreas Kamm, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Diana Burkhardt, Numerik Jena GmbH (Germany); Erik Beckert, Ramona Eberhardt, Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Advanced optical systems of telescopes and scientific instrumentation require high accuracy mounting and joining of components. Applications for deep UV, under high energetic radiation, for vacuum operation, or assemblies subjected to environmental loads (e.g. humidity and temperature) require a replacement of organic adhesives or optical cement by a more robust bonding agent. Soldering allows the bonding of different materials with an inorganic filler material.

We present the optimization of the laser-based Solder Bumping for the mounting of optical components and the parameters of the bonding process for fused silica and LAK9G15 (radiation resistant glass) with thermally matched metal mounts. The investigation covers the

experimental determination and optimization of solder wetting to the respective base materials and the achieved bond strengths. Photoelasticity measurements are used to evaluate the change in optical path difference during soldering and for different use cases. A final change in optical path difference of 3 to 5 nm is observed. The paper will conclude with a case study of lenses soldered to metal mounts with low surface deformation (less than 100 nm) suitable to high quality telescopes.

9912-137, Session P3

Every photon counts: improving low-, mid-, and high-spatial frequency errors on astronomical optics and materials with MRF

Chris Maloney, QED Technologies, Inc. (United States); Jean-Pierre Lormeau, QED Technologies, Inc (United States); Paul Dumas, QED Technologies, Inc. (United States)

Many astronomical sensing applications operate in low-light conditions; for these applications every photon counts. Controlling mid-spatial frequencies and surface roughness on astronomical optics are critical for mitigating scattering effects such as flare and energy loss. By improving these two frequency regimes higher contrast images can be collected with improved efficiency. Classically, Magnetorheological Finishing (MRF) has offered an optical fabrication technique to correct low order errors as well has quilting/print-through errors left over in light-weighted optics from conventional polishing techniques. MRF is a deterministic, sub-aperture polishing process that has been used to improve figure on an ever expanding assortment of optical geometries, such as planos, spheres, on and off axis aspheres, primary mirrors and freeform optics. Precision optics are routinely manufactured by this technology with sizes ranging from 5-2,000mm in diameter. MRF can be used for form corrections; turning a sphere into an asphere or free form, but more commonly for figure corrections achieving figure errors as low as 1nm RMS while using careful metrology setups.

Recent advancements in MRF technology have improved the polishing performance expected for astronomical optics in low, mid and high spatial frequency regimes. Deterministic figure correction with MRF is compatible with most materials, including some recent examples on Silicon Carbide and RSA905 Aluminum. MRF also has the ability to produce 'perfectly-bad' compensating surfaces, which may be used to compensate for measured or modeled optical deformation from sources such as gravity or mounting. In addition, recent advances in MRF technology allow for corrections of mid-spatial wavelengths as small as ~1mm simultaneously with form error correction. Efficient mid-spatial frequency corrections make use of optimized process conditions including raster polishing in combination with a small tool size. Furthermore, a novel MRF fluid, called C30, has been developed to finish surfaces to ultra-low roughness (ULR) and has been used as the low removal rate fluid required for fine figure correction of mid-spatial frequency errors. This novel MRF fluid is able to achieve <4Å RMS on Nickel-plated Aluminum and even <1.5Å RMS roughness on Silicon, Fused Silica and other materials. C30 fluid is best utilized within a fine figure correction process to target mid-spatial frequency errors as well as smooth surface roughness 'for free' all in one step.

In this paper we will discuss recent advancements in MRF technology and the ability to meet requirements for precision optics in low, mid and high spatial frequency regimes and how improved MRF performance addresses the need for achieving tight specifications required for astronomical optics.

9912-138, Session P3

Process improvements in the production of silicon immersion gratings

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Silicon immersion gratings improve performance and reduce spectrograph size by taking advantage of the high index of refraction (3.4) of silicon to increase dispersion and allow extensive wavelength coverage at high resolution in a single exposure. Silicon immersion gratings produced at the University of Texas at Austin provide the primary dispersive elements in the IGRINS instrument at the McDonald Observatory and the iShell instrument being built for the Infrared Telescope Facility on Mauna Kea, Hawaii, and will be used in the planned Giant Magellan Telescope Near-Infrared Spectrograph (GMTNIRS). To manufacture immersion gratings, we produce grooves in silicon using photolithography followed by plasma etching and wet etching. Our current process uses contact photolithography to pattern UV sensitive photoresist as the initial processing step. We then transfer this pattern into a layer of silicon nitride that, in turn, serves as a hard mask during the potassium hydroxide etching of V-grooves into silicon. The initial patterning of the grooves in resist is the dominant step in determining the quality of the immersion grating, and contact lithography can introduce global uniformity errors from non-uniformity in the light source and periodic errors caused by fringes in the contacting of the photomask to the substrate surface.

We have explored a number of lithographic techniques and improvements to produce the resist lines that then produce the grating groove edges. Electron beam patterning allows us to manufacture gratings that can be used in first order, with groove spacing down to 0.5 micron or smaller (2,000 grooves/mm), but could require significant e-beam write times of up to one week to pattern a full-sized grating. We are working with Jet Propulsion Laboratory to develop an alternate e-beam method that employs chromium liftoff to reduce the write time by a factor of 10. We are working with the National Institute of Standards and Technology using laser writing to explore the possibility of creating very high quality gratings without the errors introduced during the contact-printing step. Both e-beam and laser patterning bypass the contact photolithography step and directly write the lines in photoresist on our silicon substrates, but require increased cost, time, and process complexity. Finally, we have investigated anti-reflection (AR) coatings during our contact-printing lithography method to reduce the effect of fringes produced by the contact of the photomask on the photoresist surface. This AR coating reduces the amplitude of the repetitive errors by a factor of two.

9912-139, Session P3

Thermal issues related to the ion beam figuring technique when used as final step in the manufacturing of the mirror segments for the EELT

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The INAF-Astronomical Observatory of Brera (INAF-OAB) has developed a large IBF facility that is being used to investigate the problems related to the ion figuring of large Zerodur hexagonal reflecting segments, similar to those (almost 900) 1.4 m large to be realized for the assembly of the 39 m E-ELT primary mirror. It is already foreseen that the final profile correction of those segments will be done by the Ion Figuring technique. In the case of Zerodur substrates, this process has to be run quite slowly

since this material much suffer the thermal heating induced by the ion beam hitting on the mirror surface. The stresses caused in the material when heated above 120 °C can deform the final optical shape up to an unacceptable level and hence the electrical power of the ion source must be kept at a low level, with a consequent slowing down of the process that can bring to a longer than necessary time for the correction runs. The issue of the figuring time is therefore important also from the scheduling and economical point of view, especially when the number of mirrors to be processed is so large like in EELT. In INAF-OAB is under study an innovative approach to the thermal problem that has the potential to reduce substantially the figuring time of the E-ELT hexagonal segments. The results and conclusions obtained are discussed in this paper.

9912-140, Session P3

Aspherical metallic lightweight mirrors for the GCT: a prototype for the future Cherenkov Telescope Array

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The GCT (Gamma-ray Cherenkov Telescope) is a dual-mirror prototype of a Small-Size-Telescope based on a Schwarzschild-Couder optical design and proposed for the Cherenkov Telescope Array (CTA). Metallic lightweight mirrors were designed and manufactured for this prototype. The choice of this manufacturing process was made possible thanks to the relaxing optical requirements compared to those ones used for the optical telescopes. This paper describes the manufacturing process of these mirrors as well as first the results of characterisation tests.

9912-141, Session P3

Development of the fast steering secondary mirror assembly of GMT

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The Giant Magellan Telescope (GMT) will be featured with two Gregorian secondary mirrors, an adaptive secondary mirror (ASM) and a fast-steering secondary mirror (FSM). The FSM is 3.2 m in diameter and built as seven 1.1 m diameter circular segments, which are conjugated 1:1 to the seven 8.4m segments of the primary. Each FSM segment contains a tip-tilt capability for fine co-alignment of the telescope subapertures and fast guiding to attenuate telescope wind shake and mount control jitter. This tip-tilt capability thus enhances the performance of the telescope in the seeing limited mode. The design and development of the FSM mirror configuration was fully optimized and the optical performances were fully evaluated. The performance evaluation includes the optical surface deformations, image qualities, and structure functions for the gravity print-through cases, thermal gradient effects, and dynamic performances. The design and development of the FSM mirror assembly was conducted by using finite element analyses and the optical analyses. The results of the FSM mirror assembly will be compare with the optical performance goals and the dynamic performance goal of tip-tilt operation.

9912-142, Session P3

Segmentation method study for large astronomical telescope

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The primary of large ground telescopes like Thirty Meter Telescope (TMT) and European Extremely Large Telescope (E-ELT) are composed of hundreds of hexagonal segments. Because primary mirror is used to collect light, generally it has concave surface (i.e. not flat). The segments outline on this curved surface cannot be identical. There are several aspects should be considered for segmentation. They are irregularity, segment area variations, and circumscribed diameter and so on. Traditionally segmentation is ruled by a formula and solved by parameter optimization. This paper tries to present an alternative method basing on force equilibrium. By establish the connections between segmentation specifications with different forces, we can obtain a natural solution for this problem. Finally we use the new method basing TMT configuration and achieved acceptable results.

9912-143, Session P3

Stressed mirror polishing: calculation of bending forces for the successive stages of polishing

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Stressed Mirror Polishing (SMP) is a method to fabricate large aspheric mirrors in a short time. In SMP, stresses are applied to the mirror blank in order to elastically deform the desired surface into a sphere. Once the required surface accuracy is obtained upon polishing the surface to a spherical profile, the stresses are released to deform the spherical surface to the desired one.

In certain cases, if the required surface is not achieved after the release of the stresses, the process has to be repeated by calculating new values for the stress to be applied. It is found that application of new values of stress to correct certain coefficients will induce error in other coefficients during the SMP process. This paper deals with the dependencies of monomial coefficients over each other while calculating the stresses for the

successive stages of SMP. The methodology to correct these dependencies and other cross coupling between these coefficients are also discussed.

9912-144, Session P3

Mechanical technology used for bonding of the SALT edge sensors

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SALT is in the process of installing a new edge sensor system for its 91 segment Primary Mirror. Each of the 91 segment requires 6 sensor pairs. Each sensor pair utilises a receiver and transmitter printed on flexible PCB, called flexes, each of which is glued to a low Clear Ceram L-Bracket. A total of 960 flexes have to be bonded to complete the system, not counting the spare units. To meet the production schedule all sensor had to be bonded in a two month period.

The flexes have to be aligned and bonded with respect to a reference axis to within +/- 100 arc seconds and be positioned to within +/- 30 micron shear direction and +/- 100 micron in the piston direction.

The paper gives a description of the mechanical components of the edge sensor system and the bonding system design at SALT to allow us to meet the tight production goals and quality goals. It describes the quality control system used to ensure compliance with the requirement and offers recommendations for further improvements.

We also report on the actual performance of the sensors bonded in this manner. Which will be of interest to uses and developers of similar systems.

9912-254, Session P3

Manufacturing process of the WEAVE prime focus corrector optics for the 4.2m William Hershel Telescope

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In this paper, we detail the manufacturing process of the lenses that will constitute the new two-degree field-of-view Prime Focus Corrector for the William Herschel Telescope (WHT) optimised for the upcoming WEAVE Multi-Object Spectroscopy (MOS) instrument. The Prime Focus Corrector (PFC), including an Atmospheric Dispersion Corrector (ADC), is made of six large lenses, the largest being 1.1 meter diameter. We describe how the prescriptions of the optical design were translated into manufacturing specifications for the blanks and lenses. We explain how the as-built glass blank parameters were fed back into the optical design and how the specifications for the lenses were subsequently modified. We review the critical issues for the challenging manufacturing and discuss the trade-offs that were necessary to deliver the lenses while maintaining the optimal optical performance. A short description of the lens optical testing is also presented. Finally, the following manufacturing steps, including assembly, integration and alignment, are outlined.

9912-255, Session P3

Aspherization of off-axis high-asphericity mirrors with arbitrary external circuit by means of CNC machines

Aleksandr P. Semenov, Magomed A. Abdulkadyrov, Vladimir E. Patrikeev, Sergey P. Belousov, Aleksandr N. Ignatov, JSC Lytkarino Optical Glass Factory (Russian Federation)

Technology with the use of programmable computer-controlled system and a set of special instruments, which makes possible aspherization of off-axis large-size optical elements of astronomical and space telescopes with deviation from the nearest sphere of more than 1 mm, was developed.

9912-256, Session P3

Euclid mirrors and test collimator: AMOS developments

Pierre Gloesener, Fabrice Wolfs, Marcel Cola, Olivier Pirnay, Carlo Flebus, AMOS Ltd. (Belgium)

EUCLID is an optical/near-infrared survey mission to be launched in 2020 towards the L2 Lagrange point. It will aim at studying the dark universe and providing a better understanding of the origin of the accelerating expansion of the universe. Through the use of cosmological sounding, it will investigate the nature of dark energy, dark matter and gravity by tracking their observational signatures on the geometry of the universe and on the cosmic history of large structures formation.

The EUCLID payload module (PLM) consists of a 1.2 m-class telescope and will accommodate two instruments.

As a subcontractor of AIRBUS Defence & Space, AMOS is responsible for the manufacturing of the secondary and the third mirrors of the telescope as well as for the flat folding mirror set within the focal plane arrangement of EUCLID telescope, which incorporates dedicated filtering functions. AMOS produces in addition the 1.3 m-class test collimator for the on-ground validation of the EUCLID instrument.

The secondary and tertiary mirrors of EUCLID telescope are arranged in a Korsch configuration and are made from sintered silicon carbide from Boostec.

The presentation will detail the mirror manufacturing sequences, involving the CVD-SiC cladding initial step, the lapping and polishing work and the ion beam figuring operation. It will emphasize the specific constraints linked to the production of this kind of mirrors and related to the peculiar aspects of the EUCLID mission.

The corresponding mirror metrology with the accuracy budget will be outlined.

An overview of the folding mirror qualification and development will be provided with an insight into the specific spectral filtering functions brought by each mirror of the set and the associated thin film coatings developed by Schott Yverdon.

For the purpose of thermal vacuum testing and validation of the EUCLID payload, AMOS is developing a 1.3 m-class collimator.

The collimator will feature a Ritchey-Chrétien optical configuration.

The original aspect of this collimator is that it will work under a cryogenic vacuum environment at 100 K while being kept at a near-ambient temperature through an accurate thermal control involving thermal insulation, material selection and heater regulation, which will carefully be arranged to preserve the overall optical quality of the collimator.

Dedicated features of the collimator will be presented and discussed and related to the overall performance target from the EUCLID requirements.

9912-273, Session P3

Investigation of four typical groove types for use in the smoothing process

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When a surface experiencing smoothing to improve its optical performance (such as removing mid-spatial frequencies, localized grinding errors, and regional surface scratches), spindle speed, tool travel speed, pressure, slurry density as well as groove patterns are main factors to influence surface finishes. Based on the desired material removal rate, the Preston equation can effectively resolute optimized pressures and velocities between the tool and processed surface. Various groove patterns, however, can cause unique tool deformation and pressure distribution, leading to produce different slurry mobility to determine a surface finish. In this paper, four typical groove patterns are studied in this paper: non-groove, grid grove, annular groove and radial groove by using Finite Element Method (FEM) and statistical analysis. The four patterns with their optimized conditions have presented at the end of this paper.

9912-40, Session P4

Estimation of global transmitted wavefront error of the EUCLID/NISP grisms from intermediate measurements

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The Euclid mission selected by ESA in the Cosmic Vision program is a massive spectroscopic survey based on a Near Infrared Spectro-Photometer (NISP). This instrument achieves a spectroscopic mode using four grisms (standing for "grating prisms") in slitless mode. The Euclid grisms are challenging and innovative optical components based on a prism with a spherical convex face. A diffractive optical element lays on one face (mainly for the grating function) and a multilayer filter is deposited on the second face. The manufacturing process is based on three different steps: the DOE manufacturing on a parallel plate by etching process, the curved prism manufacturing and polishing, and finally, the filter deposition. At each step of this process, visible interferometric measurements are performed in order to verify the manufacturing specifications. But, the measurement of the transmitted wavefront error on the final component at operational wavelength and cryogenic environment with an appropriate accuracy is difficult to achieve. Indeed, the filter only transmits in the near infrared waveband [1250 nm-1850 nm] and the cryogenic operational temperature needed (140K) is difficult to implement during such optical tests. Therefore, the global wavefront error induces by the grism is obtained using a chain of intermediate wavefront measurements (mainly in reflection on each face). This paper presents the reconstruction of the global transmitted wavefront performance of the NISP grism, based on calculations, visible interferometric measurement and comparison to a grism optical model. This includes: the grism wavefront error budget and allocation for each manufacturing part; the zemax model of the grism made in order to compare with measurements results (especially for the DOE optical behavior); and the chosen approach to estimate the global component wavefront error (based on a sequence of relative and absolute wavefront measurements).

9912-146, Session P4

Research on error analysis of phase-retrieval holography at the Tian Ma Telescope

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The Tian Ma Telescope (TM) is the largest fully steerable radio telescope in China. It has a primary reflector of 65-m in diameter with a shaped Cassegrain configuration. It operates in a wide frequency range from 1.4 GHz to 43 GHz. The TM adopts active surface to correct the dynamic deformation due to gravity and thermal. The phase-retrieval holography will be used to measure the deformation. This paper introduces the phase-retrieval holography system at the TM, and a simulation system is implemented to find the relationship between the signal-noise ratios, defocus value, pointing errors and the measurement results.

9912-147, Session P4

Experimental verification of moment-based modal wavefront sensing

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Over the past few years, I have been investigating the moment-based modal wavefront sensing method. The focus of this investigation has been mainly on developing its basic theoretical components including the error propagation models and numerical simulation studies to understand the behavior of the method in certain measurement conditions. It has been demonstrated that this technique can be a powerful tool in various image quality / optical alignment test, especially for wide field systems and the real example has been shown where the technique was applied to the real task of assessing/driving the optical alignment of the massively replicated (i.e. 150+ identical copies) state-of-the-art astronomical spectroscopic systems called the VIRUS instrument (Visible Integral-field Replicated Unit Spectrograph). Therefore, it is fair to say that the technique is field-proven. However, the application was done in a setting where the goal was to get the job done, rather than to dig into the behavior of the technique under various (real) experimental conditions. As a result, many of the aspects and parameter spaces of the method could not be thoroughly tested or investigated. Also, there have been some not-insignificant amounts of interests among optical scientists/engineers about this particular technique. These served as my main motivation to undertake a controlled experiment to rigorously investigate the moment-based technique. This paper discusses the results of such experiment.

9912-148, Session P4

The influence of technological mounting of lightweight large size space astronomical mirrors into the shape of its reflecting surface during interferometric control

Oleg Vlasenko, Mikhail Sachkov, Institute of Astronomy (Russian Federation)

For the shape control of the reflecting surface lightweight large-size space astronomical mirrors the unweighting mirror unit is used for the neutralization of the effect of gravity on the deformation of the mirror. During the works on WSO-UV mission telescope primary mirror it was found that such a mounting has a strong influence on the mirror shape. We present the method that allows to take into account this effect. The proposed method is based on the optical surface interferometric control implementation with rotation of the mirror studied. Astigmatism and 3-point coma are main factors of mounting influence on the optical surface. The proposed method was tested on the WSO-UV primary mirror.

9912-149, Session P4

The large MEGARA pupil elements: assembly, tests, and performance

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MEGARA is a third generation spectrograph for the Spanish 10.4m telescope (GTC) providing two observing modes: a large central Integral Field Unit (IFU), called the Large Compact Bundle (LCB), and a Multi-Object Spectrograph (MOS). The instrument will be fiber-fed from the GTC Folded-Cassegrain F station to the Nasmyth-A platform of the telescope, through a collection ~44.5m length fibers of 100?m core coupled to a set of microlenses arrays arranged in two systems of 623 and 644 fiber bundles for the LCB and MOS modes respectively. Each bundle ends in a pseudo-slit at the instrument entrance. The spaxel scale is 0.62?? and the plate scale at the detector focal plane is 0.186?? per pixel (equivalent to 4-pixel resolution).

MEGARA shall work in the visible range (from 3650A to 10000A) allowing low (LR), medium (MR), and high resolution (HR) (with spectral resolving power of R = 6000, 11000 and 18000 for LR, MR and HR respectively) by means of different dispersion elements. MEGARA will provide 6 LR gratings, 10 MR and 2 HR, with the aid of a set of Volume Phase Hologram gratings (VPHs) sandwiched between two flat fused silica windows in all cases and coupled in addition to two prisms in the case of MR and HR units. The dispersive elements will be placed at the spectrograph pupil position in the path of the collimated beam.

Before the AIV and alignment, each grating unit will be subjected to several tests in order to check the requirements fulfilment. We have developed and designed several setups that will allow us to check the lines density on the grating, the diffraction efficiency and the image quality for each pupil element.

We describe the alignment procedure to be followed in the AIV process, the set of final tests and setups that will be carried out at the level of MEGARA verification (once finally assembled), and the performance results. These tests will check the top level requirements: LCB and MOS fiber links uniformity, focus position, spectral line identification, CWL and spectral coverage, FWHM and EER80, spectral resolution, instrument transmission and ghost analysis.

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Thermal testing results of an electroformed nickel secondary (M2) mirror

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To support higher-frequency operation, the Large Millimeter Telescope/Gran Telescopio Milimetrico (LMT/GTM) is replacing its existing monolithic aluminum secondary mirror (M2). The new mirror is a segmented design based on the same electroformed nickel reflector panel technology that is already in use for the primary reflector segments. While the new M2 is lighter and has better surface accuracy than the original mirror, the electroformed panels are more sensitive to high temperatures. During the design phase, concerns were raised over the level of temperature increase that could occur at M2 during daytime observations. Although the panel surface is designed to scatter visible light, the LMT primary mirror is large enough to cause substantial solar heating, even at significant angular separation from the Sun.

To address these concerns, the project conducted a series of field tests, within the constraint of having minimum impact on night time observations. The supplier sent two coupon samples of a reflector panel prepared identically to their proposed M2 surface. Temperature sensors were mounted on the samples and they were temporarily secured to the existing M2 mirror at different distances from the center. The goal was to obtain direct monitoring of the surface temperature under site thermal conditions and the concentration effects from the primary reflector.

With the sensors installed, the telescope was then commanded to track the Sun with an elevation offset. Initially, elevation offsets from as far as 40 degrees to as close as 6 degrees were tested. The 6 degree separation test quickly passed the target maximum temperature and the telescope was returned to a safer separation. Based on these initial results, a second set of tests was performed using elevation separations from 30 degrees to 8 degrees.

To account for the variability of site conditions, the temperature data were analyzed using multiple metrics. These metrics included maximum temperature, final time average temperature, and an curve fit for heating/cooling. The results indicate that a solar separation angle of 20 degrees should be suitable for full performance operation of the LMT/GTM. This separation not only is sufficient to avoid high temperatures at the mirror, but also provides time to respond to any emergency conditions that could occur (e.g., switching to a generator after a power failure) for observations that are ahead of the motion of the Sun. Additionally, even approaches of 10 to 15 degrees of angular separation on the sky may be achievable for longer wavelength observations, though these would likely be limited to positions that are behind the position of the Sun along its motion.

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Mapping the Large Millimeter Telescope primary reflector using photogrammetry: a first comparison with 12 GHz holography

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The Large Millimeter Telescope (LMT) Alfonso Serrano is a fully steerable single-dish radio telescope presently operating with a 32.5 m parabolic primary reflector. Active surface control allows for programmed correction of gravity and thermal distortions, through electro-mechanical adjustment of 84 surface segments arranged in three concentric rings. Each segment comprises 8 precision composite Nickel laminate surface panels. Panels are adjusted to the local design parabola prior to segment installation using a laser tracker. Following installation in the back-structure, initial adjustment of segments to the global parabola is accomplished using a total station and laser tracker.

The LMT project makes extensive use of holography at 12 GHz during the annual maintenance period to check and adjust the alignment of segments against the best-fit design parabola. A main drawback of the technique is the need to remove the subreflector for installation of the holography receivers at the prime focus, however this has been compatible with a desire to remove the subreflector and positioner for annual preventative maintenance. Tracker measurements have also been used for this task, however our experience shows that the technique is severely limited by environmental noise and large data collection times, on the order of many hours for a single map. In 2015 we have begun to explore the use of photogrammetry as a complimentary measurement technique. Photogrammetry can offer mapping times similar to those used for holography, at potentially higher resolution and at arbitrary elevation angles.

Accurate photogrammetry requires a robust strategy for the selection of multiple camera stations, a task complicated by the size of the antenna, obstruction of the surface by the subreflector and tetrapod legs, and the practicability of using the site tower crane as a moving camera platform. Image scaling is also a major consideration, since photogrammetry lacks an in-built distance reference, hence appropriate scale bars must be fabricated and located within the camera field of view. Additional considerations relate to the size and placement of reflective targets, and the optimization of camera settings.

In this paper we present some early results using photogrammetry to measure the primary surface of the LMT, with emphasis on the key issues mentioned above. Our results are obtained using an unmodified INCA-3 camera from Geodetic Systems Inc., with proprietary V-Stars software producing surface coordinate data. RMS surface error maps are generated from the coordinate data using in-house fitting algorithms. Laser tracker measurements of the primary surface provide a sanity check for the general performance of the photogrammetry method; an important aspect of the comparative process is the inclusion of common reference points on the surface that are measured by both techniques.

We will compare our early photogrammetry data with results from the latest holography campaign, taken shortly afterwards. We discuss the differences between data processing strategies for each method, and consider the relevance of both measurement techniques for obtaining a meaningful quantitative evaluation of the surface in terms of optical performance.

9912-152, Session P4

Day-time local phasing of neighbouring segments of the E-ELT primary mirror, based simultaneous multiwavelength shearing interferometry

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In the context of the segmented primary mirror of the E-ELT, the ability to measure the phasing state of neighbouring segments during day-time represents a way to mitigate the risk of potentially time consuming on-sky phasing after segment replacement. This paper presents the concept of a local phasing sensor based on simultaneous multiwavelength shearing interferometry, as well experimental results obtained on the ESO M1 test facility. A discussion about possible implementation scheme for the E-ELT is included.

9912-153, Session P4

Low-cost measurement and monitoring system for cryogenic applications

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Cryostats are closed chambers which maintain a high vacuum and low temperature inside, hindering the monitoring of materials, structures or systems installed therein.

This work presents webcam-based monitoring system, which can operate under vacuum and cryogenic conditions to be mainly used in astrophysical applications. The system can be configured in two different assemblies: wide field that can be used for mechanism monitoring and narrow field, especially useful in materials or structure deformation measurements with a resolution of 3 microns/pixel. Several thermal vacuum cycling tests have been performed on a prototype, showing a high reliability behavior at 80K and 10-5mbar.

A final system has been developed including some of the improvements detected in the prototype, such as: the use of a Full HD webcam to improve the resolution; an athermalized mechanical camera-cage design and an optical packed assembly, minimizing in this way the out-of-focus when the cryostat is been cooled down; an isostatic camera board holder that guaranties the perpendicularity between the detector an the lens during the whole thermal vacuum cycle and an improved fastening system and a better LED-based illumination.

A complete test campaign it is been designed to check the system performance. The paper will show the implementation of the final system, its performance and the tests results.

9912-154, Session P4

Three dimensional metrology inside a vacuum chamber

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Several three dimensional coordinates systems are proposed by companies to provide accurate measurement of mechanical parts in a volume. None of them are designed to perform the metrology of a system in a vacuum chamber. In the frame of the test of NISP instrument from ESA Euclid mission, the question was raised to perform a three dimensional measurement of different parts during the thermal test of NISP instrument into ERIOS chamber. EUCLID NISP will be tested at Laboratoire d'Astrophysique de Marseille (LAM) under vacuum and thermal conditions respectively in order to qualify the instrument in its operating environment and to perform the final acceptance test before delivery to the payload. One of the main objectives of the test campaign will be the measurement of the focus position of NISP image plane with respect to the EUCLID object plane to ensure a good focalisation of NISP instrument after integration on the payload. To simulate the EUCLID object plane, a telescope simulator will be installed in front of NISP into ERIOS chamber and focalised onto NISP detector. A metrology system shall be used to measure the position of the telescope simulator and NISP during the test campaign to determine the exact position of the NISP image plane with respect to the telescope simulator. A Metrology Verification System (MVS) has been proposed in this purpose: it is a set of metrological means

specially developed for the NISP thermal balance / thermal verification test into ERIOS vacuum chamber. The goal of the MVS is to provide at operational temperature the measurement of references frames set on the telescope simulator and NISP, the knowledge of the coordinates of the object point source provided by the telescope simulator and the measurement of the angle between the telescope simulator optical axis and NISP optical axis. The MVS concept is based on the use of a laser tracker, outside the vacuum chamber, that measures reflectors inside the vacuum chamber through a curved window. We will present preliminary results obtained during the design phase of the MVS and a preliminary test phase that shows the possibility to perform this type of measurements and the accuracy reached in this configuration. An analysis of the contributors to the measurement error budget of the MVS is proposed, based on the current knowledge of the MVS performance and constraints during the TB/TV tests. We will then propose a complete measurement error budget estimation for the MVS in the frame of NISP test campaign.

9912-155, Session P4

Measuring the elevation-dependent position of the Large Millimeter Telescope subreflector using a laser tracker

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The Large Millimeter Telescope (LMT) Alfonso Serrano is a fully steerable single-dish telescope for radio astronomy, operated jointly by the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE) in Mexico, and the University of Massachusetts Amherst (UMASS) in the US. The telescope is located in the mountainous region to the East of the Mexican altiplano, at an altitude of 4,600 m (15,092 ft). It operates without any environmental enclosure.

The LMT uses a bent Cassegrain design, comprising a 50 m parabolic primary reflector and a 2.6 m hyperbolic subreflector. The subreflector is held at the 17.5 m primary focal distance by a tetrapod structure consisting of 1.12 m diameter tubular legs that reduce to a narrower profile to minimize aperture loss. Each leg is over 27 m in length. The subreflector is supported on a hexapod for controlling movement in focus, de-center, and tilt.

A planar tertiary mirror is located on the elevation axis, 6.25 m behind the vertex of the primary parabola. Light reaches the tertiary mirror by passing through the apex cabin, a conical chamber whose entrance diameter is 2.5 m. The tertiary mirror is located on a rigid platform, attached directly to the alidade structure that supports the elevation bearings. Whilst the antenna moves in elevation, this platform provides a stable location from where one can observe the subreflector continually.

Laser trackers are used routinely at the LMT for a variety of tasks, but mostly for measuring the surface shape of the telescope optics. In this paper we present a short study of the position of the subreflector relative to the tertiary mirror and apex cabin, with distance measurements provided by a laser tracker located at the tertiary platform. The tracker beam is reflected from four corner cube targets (SMRs) located around the perimeter of the subreflector. The location of the tracker allows an uninterrupted view of all targets during full movement of the antenna in elevation, and at the same time provides a stable point from which to take measurements. As the tracker is effectively located inside the receiver cabin, a high degree of protection is afforded against the elements. This consideration is important since the equipment is operating outside the manufacturer's environmental specifications.

The results are analyzed with the aim of checking for relative motion of the subreflector resulting from gravitational and/or thermal deformations of the antenna structure. We discuss the precision of this measurement technique, carried out using a high-accuracy commercial laser tracker and compare these experimental values with predictions from the structural model. While the exclusive use of a laser tracker may be considered overkill for a longer-term monitoring exercise, one might easily consider the employment of simpler, line-of-sight distance measuring devices.

9912-157, Session P4

Temperature measurement and thermal deformation analysis on the alidade of TM65m

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Aimed at the alidade of TM65m, 14 key joints were installed thermal sensors to map the distribution of temperature. The variation laws of the temperature with time of day and season were statistically analyzed. The largest temperature differences of the joints and four surfaces of each point were obtained. Furthermore, the measured joint temperatures were applied on the finite element model to analyze the thermal deformations of the alidade. At the same time, an inclinometer was installed on near one of the elevation axis to get thermal gradient information on the alidade deformation. The results of measurement and finite element analysis will provide basis for the pointing model modification.

9912-158, Session P4

Hollow-cathode lamps as optical frequency standards: the influence of optical imaging on the line ratios

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In recent years hollow cathode discharge lamps (HCLs) have been successfully used as a source for calibration of optical astronomical spectrographs. The numerous narrow metal lines are well suited for a m/s calibration accuracy of high-resolution spectrographs, while the gas lines are Doppler broadened and may not be used. Accordingly, one of the crucial issues is the strength ratio of metal to buffer-gas lines which is measured after the HCL is imaged onto the spectrograph entrance. However, the processes inside the lamp cause the light to be emitted from different regions between the cathode and anode. As a consequence different beams are emitted. We used four different HCLs to measure and characterize these beams with respect to their spatial distribution, their angle of propagation relative to the optical axis and their line-strength ratios. The model that we used to fit the measured beams allows us to predict the line-strength ratios available for different optical configurations. The lamps we used in this study were filled with either Argon or Neon as a buffer gas, and the cathode material consisted of either Uranium or Thorium embedded in a matrix material.

9912-159, Session P4

Alignment of the ESPRESSO Coudé train on the ESO VLT

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ESPRESSO (Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations) is a high resolution UV-Vis spectrograph that will be placed in the combined Coudé laboratory of the ESO VLT. The instrument is in its assembly phase and the Coudé optics will start to be mounted at the telescope in the first quarter of 2016. This paper describes the optics of the train and the strategies for its alignment taking into account the main constraints: accessibility, mechanical, as per built optics tolerances and tools.

9912-160, Session P4

Eliminating interferometric alignment error based on digital Moire technique

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Large-aperture optical surfaces with very low figure error are adopted in astronomical telescopes. Interferometry is among the most accurate and popular methods for optical surface measurement. The accuracy of the interferometry relies on many key techniques, including frequency stabilization, violation isolation and also precise alignment of the optical system. If the elements inside the interferometer are not positioned at the designed places, measurement error will be introduced due to aberration.

Currently the alignment of interferometer is realized with high-accuracy mechanical stage, alignment symbol and laser ranger. Once the interference pattern reaches the sparsest or the peak-to-valley (PV) value of the measured wavefront reaches the minimum, the interferometer is well-aligned. That is because the fabrication error of the system (including the figure error of the measured surface) is determined for a specific optical system and will not change with the alignment. Only when the alignment error is 0 compared with the designed position, the PV value of the wavefront will be the smallest and only include the influence of fabrication error. We define the 0 alignment error position to be best alignment position. Generally the position and attitude of the measured surface is adjusted with complicated mechanical stages gradually and finally reaches the best alignment position.

In this paper, we propose an alignment error elimination method based on digital Moire technique. We create a virtual interferometer with simulation software. The virtual interferometer contains optical elements with nominal parameters and positions. Standard phase-shifting interferograms are generated with the simulation. For the actual interferometer, after coarse alignment, only one shot of the interferogram is taken. Then digital Moire technique is used to combine the virtual and actual interferograms. The corresponding Moire fringes carry the information of the difference between virtual and actual wavefront, which is affected by both fabrication and alignment error. In the next step, we do not adjust the actual interferometer any more, but gradually adjust the position and attitude of the measured surface in the virtual interferometer. We continue calculating the wavefront difference between actual and virtual interferometer. And when the PV value of the wavefront difference reaches the minimum, we consider the position and attitude of the measured surface in the virtual interferometer matches that in the actual interferometer. And the wavefront difference is free from alignment error and can be used directly for figure error solution.

The fine alignment of measured surface is done in the software and no accurate mechanical device or complicated alignment symbol is necessary. Moreover, only one shot of actual interferogram is taken, so the influence of vibration can be avoid.

The detailed principle of the alignment error elimination method will be proposed, followed by demonstration with simulation and real measurement experiments. The final influence of alignment error to figure error measurement can be reduced to less than 1/30 of the wavelength even when the coarse alignment only reaches accuracy of several millimeters.

9912-161, Session P4

Pyramid wavefront sensor for image quality evaluation of optical system

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Based on the theory of the pyramid wavefront sensor, we are going to develop a simulation software and a wavefront detector which can be used to test the imaging quality of the telescope. In our system, the sub-pupil image intensity through the pyramid sensor is calculated to obtain the aberration of wavefront where the piston, tilt, defocus, spherical, coma, astigmatism and other high level aberrations are separately represented by Zernike polynomials. And the imaging quality of the optical system is then evaluated by the subsequent wavefront reconstruction. The performance of our system is to be checked by comparing to the measurements carried out using Puntino wavefront instrument (the method of SH wavefront sensor). Within this framework, the measurement precision of pyramid sensor will be discussed as well through detailed experiments. In general, this project would be very helpful both in our understanding of the principle of the wavefront reconstruction and its future technical applications.

9912-162, Session P4

VUV optical ground system equipment and its application to the ICON-FUV flight grating characterization and selection

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ICON (Ionospheric Connection Explorer) is a NASA mission which aim is to understand how Earth's space environment is impacted by terrestrial climate. In the framework of this project, a facility for the characterization of the FUV (Far Ultra-Violet) instrument has been designed and developed at the Liège Space Center (CSL). FUV is a two channel spectrographic imager, that measures intensity and spatial distribution of oxygen (135.6 nm) and molecular nitrogen (157 nm). Those wavelengths are strongly absorbed by the atmosphere and the optical elements of the system have to be tested inside a vacuum chambers.

The facility is composed of a vacuum monochromator that can either be illuminated with a calibrated deuterium lamp source (with a wavelength range of 115 to 180 nm) or a fiber coupled visible light source for alignment, verification purposes and visible spectral analysis. Two selectable gratings

can be used to maximize throughput in each region of the spectrum (visible and UV). The second part of the installation is a vacuum collimator assembly based on an off-axis parabola which produces approximately a 10 cm diameter collimated beam. As the instrument is placed on a precise tip/tilt/rotation manipulator, each region of the instruments field of view can be addressed by the beam. The Optical Ground System Equipment has special useful features such as in situ control of the beam spatial homogeneity with calibrated detectors.

Prior to the instrument test, two 3600 ln/mm gratings were tested in order to check the diffraction efficiencies and select which one is the best and will become the flight instrument grating if there were any difference. The facility was adapted for this experiment. We used a well collimated beam and reduced its size to 1 cm diameter. For the purpose of the test, the plane of the grating is centered with the collinear rotation axes of two rotation stages. One rotation is dedicated to the detection, and gives the measured diffracted light intensity with respect to its angular position. The grating is fixed to a second rotation stage and thus allowed to modify the beam incidence angle on the grating. The grating was placed on two rotation stages in order to scan different locations of the grating. This adapted set up permitted to measure diffraction efficiencies and scattering properties at vacuum UV wavelength.

We present the simulation motivated design that lead us to build such a facility. Then we will give the results of the grating measurements. A discussion on the obtained result and their implication for the instrument will be given.

9912-163, Session P4

Singular values behaviour optimization in the diagnosis of feed misalignments in radioastronomical reflectors

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The high performance required to modern radio telescopes as well as to large reflector antennas exploited to communicate with interplanetary probes asks for the monitoring of the antenna status, in terms of misalignments of the optical chain (primary reflecting surface, sub-reflector, if present, and feeding system) and/or of deviations from the nominal shape of the primary surface due to misplacements of the panels, in the case of panelled reflectors. The monitoring can be required at the installation stage as well as during the whole antenna lifetime, to guarantee the periodical reassessment of the instrument.

During the years, different approaches have been proposed to retrieve the antenna status. In particular, a convenient one is indirect, based on the measurement of the antenna Far-Field Pattern (in amplitude and phase, or in amplitude only) [1,2]. Indeed, those misalignments which are compatible with the measurements, i.e. those misalignments producing, according to the adopted electromagnetic model, a Far-Field Pattern (FFP) as close as possible to the measured one, can be assumed as the ones affecting the instrument. A full data set describing the FFP at the Nyquist rate is typically used in the diagnosis procedure, in both cases the amplitude only, and the amplitude and phase acquisitions. Unfortunately, for large electrical antennas, the number of FFP points, covering the whole visible range, is very large, resulting in very lengthy measurement processes, subjected to variations of environmental conditions, affecting the correlation among the collected data, and to an involved acquisition scheme determined by the complex tracking of the source.

The aim of the communication is to present an innovative method allowing the diagnosis in the case of amplitude and phase acquisitions, optimizing the number of FFP data by tailoring the number and the distribution of measured field samples to the desired monitoring goal. The approach is here referred to the feed misalignment reconstruction, and rephrases the antenna monitoring as the determination of the Aperture Field (AF) from the FFP, giving the result from AF thanks to Geometrical Optics considerations. The exploited AF model introduces the effects of the feed misplacement on the nominal AF in terms of an aberration function, expanded to the order compatible with the estimated maximum deviation of the feed position from the nominal one. The AF reconstruction from the FFP is formulated as an inverse problem, linearized thanks to a Principal Component Analysis on the perturbation factor of the nominal AF. The number and the positon of the field samples are then determined by optimizing the Singular Values behaviour of the relevant linear operator.

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9912-164, Session P4

Rebuilding the spare Oxford SWIFT spectrograph camera

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SWIFT is an I and z band integral field spectrograph on the 200 inch Hale Telescope at Palomar Observatory. The off-axis image quality is not as high as expected from the optical design, and it is not certain whether the lens mounting technique or optical misalignments are causing this problem.

To investigate this, the spare SWIFT spectrograph camera was rebuilt using new lens mount designs developed for the HARMONI spectrograph that are adhered to the edge of the lenses rather than clamped to the face, which should decrease any stress on the lens. These mounts also use the mount as a mechanical reference rather than the optic, which should minimize the risk of damaging the lens.

The camera was interferometrically tested at a range of field angles across the whole field of view with both the original and updated lens mounting schemes to measure the optical performance and determine whether the new lens mounting scheme should be used in future instruments.

9912-165, Session P4

High precision breadboard for integrations of the NISP/EUCLID focal plane

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The instrument NISP (standing for Near Infrared Spectro-Photometer) is one of the two instruments of the Euclid mission which was selected by ESA in the framework of the Cosmic Vision program. NISP will combine a photometer and a spectrometer working in the near-IR (0.9-2 microns). Its detection subsystem (called NI-DS) is based on a mosaic of 16 IR detectors cooled down to 95K while the front-end readout electronics will be kept at 140K. The detectors will be integrated on a mechanical focal plane made of Molybdenum and Aluminum while a panel in Silicon Carbide (SiC) allows to interface the NI-DS with the rest of NISP.

In this context, we have developed a specific and modular breadboard with a direct interface with the SiC panel aiming at supporting the NI-DS flight model FM during each step of its development from integration to validation at room temperature. Therefore, this tool has to cope with a large range of uses: in particular, it has to be stable during long period of time (for the integration phases), to allow the handling of the NI-DS (in various configurations and orientations), to be compatible with ISO5 and vacuum environments.

On top of that, the interface with the SiC panel of the instrument has imposed a very stringent specification on the flatness at the interface i.e. below 5 microns PV on a quarter square meter. This specification was verified by using a dedicated optical metrology which allowed us to reach the required accuracy (<0.5 microns) over the entire surface.

In this article, we will describe the functions and the design of this breadboard, the manufacturing process and the optical controls applied during its acceptance. We will also describe the validation campaign based on vibrations tests performed at the Laboratoire d'Astrophysique de Marseille (LAM) on a representative model of the NI-DS.

9912-166, Session P4

Alignment and metrology plans for the GESE telescope and instruments

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The Galaxy Evolution Spectroscopic Explorer (GESE) requires a 1.5-m class wide field space telescope coupled with a visible light imager and ultraviolet multi-object spectrograph.

This paper defines the technical challenges of the optical metrology and alignment for this system. A proposed solution that includes laser metrology and incorporates computer generated holograms is presented and discussed.

9912-167, Session P4

Fabrication and testing of large lenses for modern astronomical telescopes

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Modern telescopes require increasing difficult optics. While the challenges and technical solutions for fabricating and testing the telescope mirrors are well known, the large field corrector lenses also require advances in technology. The lenses are larger, more highly aspheric, and have tighter performance requirements than ever. This paper defines the difficulty of manufacturing large lenses and discusses some technical advances, including support, grinding, polishing, and metrology that make it possible.

9912-257, Session P4

Errors analysis of dynamic stitching interferometry

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Interferometry is the common method for measuring high precision optical elements. In order to extend the testing region and lateral resolution, an effective technology subaperture stitching is proposed to overcome the aperture size limitation of conventional interferometers. The combination of them is an efficient and economical way for measuring large optical flat, which is widely used in high-power laser system and astronomy. The large flat can be measured many times on different positions to get subaperture data, and then stitch them together to reconstruct full aperture surface.

In situ measurement is indispensable and effective for fabrication of large optical elements. It does not need moving and remounting the workpiece, which could reduce errors in testing and further guide the next manufacture. In situ means the workpiece stay in the fabricating position and measurement in workshop. The environmental disturbance is the most troublesome. Commonly commercial phase-shifting interferometers are not suitable for the vibrating environment. Thus some dynamic interferometers are invented and hoped to be employed in that condition gradually. We have built an experimental system to simulate in situ measurement for large plane mirror in workshop, which combine dynamic interferometer and multi-aperture stitching measurement technology. It includes dynamic interferometer, the interferometer support and a two-dimensional mobile platform and so on. Dynamic interferometer is placed on the interferometer support, and the measured component is placed on the two-dimensional mobile platform, which can achieve both horizontal and vertical directions of translation. In this dynamic interferometer, spatial carrier interferogram is taken and Fourier transformed to obtain the wavefront.

The moving uncertainly of this mobile platform has to be analysed in this paper. Straightness in different directions will introduce tip tilt or rotation in subaperture data, and positioning accuracy will decreased the stitching accuracy. We analysis the impact of these errors on the measurement results and proposed corresponding restrained method. The validity of this method is verified by an optical flat with size 200mm?300mm on above experimental system.

9912-168, Session P5

The integrated opto-mechanical FEA analysis for Large Space Telescope

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The technology of integrating mechanical FEA analysis with optical estimation is essential to simulate the gravity deformation of large main mirror and the thermal deformation such as static or temperature gradient of optical structure. We present the simulation results during the process of FEA analysis, data processing, and image performance. Two kinds of supporting ways for large main mirror which has the center holding structure or the edge glue fixation, are designed and compared to get the optimal gravity deformation. Variable mirror materials Zerodure/SiC are chosen and combined with different structure materials titanium alloy/indium steel/silicon aluminum alloy, to obtain the small thermal gradient distortion. The simulation accuracy is dependent on the shape and number of FEA net nodes, the border definition of structure, the fitting error from discrete data to smooth surface. The relation between nodes number and fitting error is figured, and the suitable nodes number is proposed when making the FEA analysis. As a main mirror of 1m diameter as an example, the appropriate structure material to match mirror, the central supporting structure, and the key aspects of FEA simulation is achieved for space application.

9912-169, Session P5

Tolerancing of a carbon fiber reinforced polymer metering tube structure of a high-resolution space-borne telescope

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High resolution space borne telescopes require dimensionally stable structures to meet very stringent optical requirements. Furthermore, high resolution space borne telescope structures need to have high stiffness and be lightweight in order to survive launch loads. Carbon fiber reinforced polymers (CFRP) are lightweight and have tailorable mechanical properties like stiffness and coefficient of thermal expansion. However, mechanical properties are highly dependent on manufacturing processes and manufacturing precision. Moreover CFRP tend to absorb moisture which affects dimensional stability of the structure in the vacuum environment. In order to get specified properties out of manufacturing, tolerances need to be defined very accurately.

In this paper, behavior of CFRP metering tube structure of a high resolution space borne camera is investigated for ply orientation, fiber and void content deviations which may arise from manufacturing errors and limitations. A computer code is generated to determine laminate properties of stacked up uni-directional (UD) laminae using classical laminate theory with fiber and matrix properties obtained from suppliers and literature. After defining lamina stack up, many samples are virtually created with ply orientations, volumetric fiber and void content that randomly deviates in a tolerance range which will be used in manufacturing. Normal distribution, standard deviation and mean values are presented for elasticity modulus, coefficient of thermal expansion (CTE), coefficient of moisture expansion (CME) and thermal conductivity in axial and transverse directions of quasi-isotropic stack ups and other stack ups which have properties presented in literature.

9912-170, Session P5

TCS and peripherals robotization and upgrade on the ESO 1 meter telescope at La Silla Observatory

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We describe in this work the robotization and upgrade of the ESO 1m telescope located at La Silla Observatory. The ESO 1m telescope was installed in La Silla in 1966. It will host FIDEOS, a high resolution spectrograph designed for precise RV measurement on bright stars. In order to meet this project's requirements, the TCS (Telescope Control System) and some of its mechanical peripherals needed to be upgraded. The old synchronous motors were replaced by steppers and DC motors with encoders added on. The Dome rotation and opening system was also integrated into the control system by modifying the old interface, encoders and limit switches. The telescope's shutter was modified changing its synchronous motors with modern stepper motors, but using the old mechanical interface. In order to improve the telescope's precision we added on-axes encoders to the system, which dynamically compensate within a PID control system the natural backlash and periodical errors inherent to these mechanical setups. The TCS was also upgraded into a modern and robust control system mounted on a group of Raspberry PI single board computers interacting together as a computer network with the CoolObs TCS board developed by Obstech. One of the particularities of the CoolObs TCS boards is the fact they allow to fuse the input signals of 2 encoders per axis in order to achieve a high precision and resolution with moderate cost encoders. The TCS also was integrated with the FIDEOS control system, so all the system can be controlled through the same remote user Interface. The modern TCS allows the user to run observations remotely through a secured internet web interface, minimizing the need of an onsite observer. We will show how this system improved the telescope's pointing and tracking on the FIDEOS commissioning. We also illustrate the main system's usability in detail.

9912-171, Session P5

Error compensation research on the focal plane attitude measurement instrument

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The surface accuracy of astronomical telescope focal plate is a key indicator to precision stellar observation. Combined with the six DOF parallel focal plane attitude measurement instrument that had been already designed, space attitude error compensation of the attitude measurement instrument for the focal plane was studied in order to measure the deformation and surface shape of the focal plane in different space attitude accurately.

Position and attitude accuracy of the six DOF parallel focal plane attitude measurement instrument is one of the main factors which affect the quality of its work. In order to ensure the accuracy of attitude measurement and reduce the measurement error, first, zero calibration of each axis on the platform was done by a variety of methods. And the calibration stability was measured by dial indicator and magnetic table and the optimum calibration mode was obtained. Then the terminal attitude of the platform was measured by the high precision angle measurement instrument and the error data sample was analyzed. Based on the radial basis function (RBF) neural network compensation algorithm, a three layer RBF neural network model was established which took the actual attitude angle as input and the desired attitude angle as output. On the basis of the model, error compensation for the focal plane attitude measurement instrument through the experiment was carried out. The feasibility of the method to error compensation was verified.

9912-172, Session P5

Research and implementation of the integrated cooling system for focal plate

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With the rapid development of multi-objective astronomical survey telescope technology, the heat of focal plate which high-density optical fiber positioners were mounted in has become the key factor of system precision. The new integrated cooling system designed multi curved composite grooves on the surface of focal plate for forced convection was proposed. Meanwhile, the manufacturing process, sealing structure and heat dissipation performance of the system were analyzed and tested with detail in the paper. The experimental results suggested that the new integrated cooling system of focal plate has a fast response speed and good heat dissipation performance.

The multi curved composite grooves are located in the gap on the focal plate surface with hole array, which should not only to meet the requirements of heat dissipation and space of high-density optical fiber positioners, but also to solve the problem of manufacturing and sealing in the narrow space of the focal plate, and to maintain mechanical properties of the whole system at the same time. The focal plate was modeled by

CAD software and its stiffness was analyzed by finite element software. The simulation of focal plate transient temperature field was carried out in different convection coefficient, different water mean temperture which flowed through the grooves and different number and distribution of grooves on the surface of focal plate. The model of focal plate cooling system was optimized after comparing and analyzing the simulation results and studying each variable effect on focal plate temperature field. At last, the model of the focal plate was fabricated and the experimental platform of cooling system was built. The pressure and sealing of the focal plate are tested, then the experiment was carried out the validate validity of simulation results. Experimental results suggested that the designed integrated cooling system is mainly in agreement with the simulation results. The cooling system can ensure the temperature field of whole focal plate stabled. The temperature in the experiment shows uniform distribution during the course of an observation. The temperature change of whole focal plane can be controlled in a constant range.

9912-173, Session P5

Mechanical performance of the GCT: a dual-mirror telescope prototype for the future Cherenkov Telescope Array

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The Cherenkov Telescope Array (CTA) project aims to create the next generation Very High Energy (VHE) gamma-ray telescope array. It will be devoted to the observation of gamma rays from 20 GeV to 300 TeV. Because of this wide energy band, three classes of telescopes, associated to different energy ranges and different mirror sizes, are defined. The Small Size Telescopes (SSTs) are associated to the highest energy range. About 70 of these telescopes are foreseen on the Southern site of the CTA. The large number of telescopes constrains their mechanical structure because easy maintenance and reduced cost per telescope are thus needed. Moreover, of course, the design shall fulfil the required performance and lifetime in the environment conditions of the site.

The Observatoire de Paris started in 2011 design studies of the mechanical structure of the GCT (Gamma-ray Cherenkov Telescope), a four-meter prototype telescope for the SSTs of CTA, from optical and preliminary mechanical designs made by the University of Durham. At the end of 2014 these studies finally resulted into a lightweight (~8 tons) and stiff design. This structure was based on the dual-mirror Schwarzschild-Couder (SC) optical design, which is an interesting and innovative alternative to the one-mirror Davies-Cotton design commonly used in ground-based Cherenkov astronomy. The benefits of such a design are many since it enables a compact structure, lightweight camera and a good angular resolution across the entire field-of-view. The mechanical structure was assembled on the Meudon site of the Observatoire de Paris in spring 2015 and the Telescope Control System was successfully implemented at the end of the year 2015 leading to a fully operational telescope.

This paper focuses on the mechanics of the telescope prototype. It describes the mechanical structure and presents its performance identified from computations or direct measurements. Upgrades of the design in the context of the pre-production and the large scale CTA production are also discussed.

9912-175, Session P5

Design of the telescope controller rejecting ground base disturbance

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In this paper, a telescope controller design method rejecting ground base disturbance is proposed. Telescope systems usually suffer some uncertain disturbances. One of these is the disturbance come from ground base. Unlike the other disturbances, such as wind load, friction etc. The ground base disturbance can hardly be rejected by improve the bandwidth of control system. This paper gives the measurement of the influence to the telescope coming from ground base disturbance. The property of ground base disturbance to the control system is concluded. Then, a control method is proposed. Finally the experiment result is proposed.

9912-176, Session P5

Detachable external telescope for mobile phone

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Mobile phone has been a popular thing in life because of its many functions except making a call, such as camera, recorder, and so on. In fact, it has replaced normal digital camera gradually due to its high quality device, for example, CMOS and its lens. But it is difficult to catch a photo of a long distance object, comparing the normal digital camera as its lens is specially designed for conditional object instead of a long distance object. We have already designed and made an external wide angle lens for mobile phone successfully .This paper introduces a detachable external telescope for mobile phone. The external telescope system is designed to work with the mobile phone' own lens. It can be used to observe and take a photo of long distance object directly, even for the surface of the moon. The telescope drawtube is divided into two parts to connect easy and portable. Its objective lens uses doublet structure. Its strict spherochromatic aberration correction makes the image quality correction more excellent. The lens diameter is 60mm to ensure the light, bright image. The diameter of its ultra-wide-angle eyepiece lens is 22mmand the focal length is f=25 mm. Large eyepiece ergonomic design makes it more comfortable. The telescope system has a focal length of 700mm. It is not only enough to ensure high resolution imaging and but also to obtain higher multiples. Combining with the lens in mobile phone, image from a long distance, e.g. moon surface, can get clearly. In the mechanical structure, the length of the system along the axial is about 800mm. In order to facilitate carrying, the telescope tube is designed to be detachable structure of two part, which can be connected by a fastener immediately. The mechanical structure of eyepiece is designed reasonably to ensure that the system and mobile phone lens are coaxial and can be connect quickly.

It is an external accessary for the mobile phone to make the mobile phone more powerful. The system was designed for two kind of usage: one is the observation by human eye with a special lens in telescope, another is recording the image by the camera in the mobile phone simultaneously. After optimization of design, this moon telescope system has small size, light weight, easy to carry.

9912-258, Session P5

Advancements in strain matching of optical materials (glass and silicon carbide) with composite material metering structures

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The historic approach for developing space borne optical systems has been to match the CTE of the optical components with the CTE of the metering structure. Polymer based composite materials are typically baselined as the structural material of choice when low CTE glass is selected as the optical material of choice as they offer benefits regarding minimizing mass and maximizing stiffness. Tailored composite material systems and near zero CTE glass materials such as ULETM and ZerodurTM achieve near zero CTE across temperatures near room temperature. However, for applications where there are larger operational temperature exposures, it becomes more desirable for the dL/L curves of the materials to match or track each other. Improvements in both composites and glasses are improving this matching of the dL/L behavior of the materials. Another very promising materials development is the CTE and dL/L matching of a new composite material system with Silicon Carbide (SiC) optical materials. When SiC optics have been selected, this new composite material system may be desirable to serve as the structure to meter the SiC optics. The use of this material avoids fracture mechanics concerns of using SiC as the metering structure, particularly in larger applications.

This paper summarizes some the work that has been done to address CTE and thermal strain matching of polymer composites to the more commonly used Glass optical materials and Silicon Carbide optical materials for satellite and aircraft applications.

9912-259, Session P5

Development of a 0.5m clear aperture cassegrain type collimator telescope

Mustafa Ekinci, Ozgur Selimoglu, TÜBITAK UZAY (Turkey)

Collimator is an optical instrument used to evaluate performance of high precision instruments, especially space-born high resolution telescopes. Optical quality of the collimator telescope needs to be better than the instrument to be measured. This requirement leads collimator telescope to be a very precise instrument with high quality mirrors and a stable structure to keep it operational under specified conditions. In order to achieve precision requirements and to ensure repeatability of the mounts for polishing and metrology, opto-mechanical principles are applied to mirror mounts. Finite Element Method is utilized to simulate gravity effects, integration errors and temperature variations. Finite element analyses results of deformed optical surfaces are imported to optical domain by using Zernike polynomials to evaluate the design against specified WFE requirements. Both mirrors are aspheric and made from Zerodur for its stability and near zero CTE, M1 is further light-weighted. Optical quality measurements of the mirrors are achieved by using custom made CGHs on an interferometric test setup. Spider of the cassegrain collimator telescope has a flexural adjustment mechanism driven by precise micrometers to overcome tilt errors originating from finite stiffness of the structure and integration errors. Collimator telescope is assembled and alignment methods are proposed.

9912-260, Session P5

Two approaches to thermal dimensional stability for spaceborne mirrors

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Two material approaches to thermal stability are in practice today for spaceborne missions. A. The first uses materials with high thermal expansion and high thermal diffusivity. Since these materials respond to a transient rapidly and equalize, the thermal distortion on the optical surface is mitigated. B. The second uses materials with very low thermal expansion, inevitably accompanied by low thermal diffusivity. The small thermal expansion mitigates distortion even though the diffusion time is longer. Ideally the material would have low thermal expansion and high diffusivity. Unfortunately no such material is available. We will compare the thermal stability response of comparable systems in both a low and high earth orbit.

9912-177, Session P6

On the origin and removal of interference patterns in coated multimode fibres

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Integral Field Units (IFUs) are now widely used on large telescopes for three dimensional spectroscopy. These instruments have a complex design and, although their bulk properties are well known, there are subtle effects that need to be investigated to optimise their use and data reduction.

Such is the case for the VIMOS-IFUs, where variable interference patterns (fringing-like) have been reported and were not clearly explained until now. These interference patterns affects the spectra in the visible wavelengths.

At the focal plane of a telescope, the whole IFU, including the core, cladding and coating of each fibre, is illuminated. This coating is a polymer used not only to protect the glass of the fibre from the harsh environment, but it also has a higher refractive index to strip the cladding modes.

We present experimental results of interference patterns produced in multimode fibres coated with polyimide, the preferred coating material for the fibres used for IFUs. Our experiments show that, under some conditions, cladding modes are interacting with the polyimide coating producing interference in the output spectrum. Also we show that as the fibre is manipulated, the interference pattern changes, therefore the fibres should be carefully managed in order to minimize this potential problem for the instruments. Finally we also present a simple way of modelling this interference pattern, which can be included in the data reduction pipeline to remove this pattern from spectra ranging from the visible to the near infrared.

These results should be of interest for an optimisation of the data reduction pipelines. Moreover, understanding the effects of the different technologies will benefit innovations and developments of fibre systems.

9912-178, Session P6

Effects of fiber manipulation methods on optical fiber properties

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Optical fibers are now routinely used to couple high-resolution spectrographs to modern telescopes, enabling important advantages in areas such as the search for extrasolar planets using spectroscopic radial velocity measurements of candidate stars. Optical fibers partially scramble the input illumination, and this phenomenon enables a fiber feed to provide more uniform illumination to the spectrograph optics, thereby reducing systematic errors in radial velocity measurements. Current instruments now achieve a precision of ~1m/s using fiber-feeds, but greater precision approaching 10cm/s is required to detect terrestrial planets orbiting sun-like stars. A primary limiting factor in multimode fiber coupling is modal noise, a measurement uncertainty caused by inherent properties of optical fibers, evident as a varying spatial intensity at the fiber exit plane. Many instruments utilize the strategy of agitating the fiber during an observation to reduce modal noise, and squeezing of the fiber and dynamical optical diffusers have been tested as alternatives to agitation. However, deformation of the fiber can lead to light loss, and diffusers may be suitable only for calibration sources due to significant known losses. The technique of stretching or varying the length of the fiber has been shown to offer advantages over other approaches, including potentially greater uniformity of the exit intensity distribution. But effects of stretching on fiber parameters such as total transmission and focal ratio degradation have not been adequately studied. In this paper we present results of measurement of transmission loss and focal ratio degradation in a stretched fiber, along with discussion of possible consequences.

9912-179, Session P6

Influence of misalignment on output of astronomical large-core fibers of multi-object fiber spectroscopic telescopes

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Large-core fibers are wildly used in astronomical applications. For multi-object fiber spectroscopic telescopes, for example the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST), the aiming accuracy is important. The fibers in these telescopes have two ends; one input end is in the focal plane to collect the star image while another output end is inside a spectrometer.

If the input end doesn't exactly match the image of the star, the emitting spot from the output end could not be a central-peak circular spot. If the misalignment is serious, the output would be a ring. The ring spot would lead to wrong spectrum analysis result. To obtain the relationship of the input position and the output spot, we designed a scanning experiment. We chose a single-mode fiber for 650nm, which core diameter is 4 m, to scan a large-core astronomical fiber FBP320385415 of 320m core diameter, which is used in LAMOST. The light source was a laser diode, so the emitting spot from fiber had serious speckles. The strong speckles made it very difficult to fit the output spot to a certain shape. We introduced a fiber-vibration system to average the speckle patterns, then we can get much smoother output patterns.

The experimental results show that the output spot will be a ring spot instead of the supposed circular pattern, when the input point is 122m away the center of the fiber. The nearer of the input position is to the edge of fiber, the closer the output spot to a ring. A energy ratio function is proposed to describe the level from a circular spot to a ring. The peaks of energy ratio function correspond the dividing line between the circle spot and the ring spot. This experimental result is important for designing and optimizing the fiber-end adjusting devices of multi-object fiber spectroscopic telescopes.

9912-180, Session P6

Back-illuminate fiber system research for multi-object fiber spectroscopic telescope

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Using parallel controlled fiber positioner as the spectroscopic receiver is an efficiency observation system for spectra survey, has been used in LAMOST recently, and will be proposed in CFHT and rebuilt telescope Mayall. In the telescope observation, the position of fiber will highly influence the spectra efficient input in the fiber to the spectrograph. When the fibers were back illuminated on the spectra end, they would export light on the positioner end, so the CCD cameras could capture the photo of fiber tip position covered the focal plane, calculates the precise position information by light centroid method and feeds back to control system. After many years on these research, the back illuminated fiber measurement was the best method to acquire the precision position of fibers. A set of fiber back illuminated system was developed which combined to the low revolution spectro instruments in LAMOST. It could provide uniform light output to the fibers, meet the requirements for the CCD camera measurement and was controlled by high-level observation system which could shut down during the telescope observation. The paper was introduced the back illuminated system design and different test for the light resource. After optimization, the effect illuminated system could compare the integrating sphere, meet the conditions of fiber position measurement.

9912-181, Session P6

A compact optical fiber positioning device

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In this paper, a compact optical fiber positioning device is proposed, which is especially suitable for small scale and high density fiber positioning. Based on the positioning principle of double rotation, positioning device's center shaft depends on planetary gear drive principle, meshing with the fixed annular gear central motor gear drives device to rotate. The eccentric shaft is rotated by a coaxial eccentric motor. Both center and the eccentric shaft are supported by a rolling bearings. The center and eccentric shaft were designed with electrical zero as a reference point, all of them have position-limiting capability to ensure the safety of fiber positioning. The eliminating clearance with spring structure were combined in the eccentric and center shaft, which could eliminate the influence of gear gap. The driving circuit could be installed in the positioning device's body for two driving motor. Another excellent improvement design is the favorable heat sink, the heat bring by positioning operation can be effectively transmit to design a focal plane unit through the aluminum component. There are

cooling spiral airway integrate on positioner sleeve, when positioning, the cooling air flow is inlet into the unit hole on the focal plate, the cooling air flow can effectively take away the positioning's heat, which extremely eliminate the impact of the focus seeing. After experiment measured the prototype design of new fiber positioner, the results show that: the unit accuracy reached 0.01mm, which could meet the requirement of fiber positioning.

9912-182, Session P6

Research of subdivision driving technology for brushless DC motors in optical fiber positioning

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In fiber spectroscopic telescopes, optical fiber positioning units are used to position thousands of fibers on the focal plane quickly and precisely. Stepper motors are used in existing units, however, it has some inherent deficiencies, such as serious heating and low efficiency. In this work, brushless DC motors without these disadvantages are employed instead of stepper motors in the developing optical fiber positioning units. Nevertheless, due to its own structure feature, brushless DC motor cannot meet the unit's demand of positioning accuracy and resolution in conventional driving methods. Therefore, the universally adopted subdivision driving technology for stepper motors, which can effectively improve the positioning accuracy and resolution, is transplanted to brushless DC motors. In brief, this research mainly focuses on develop a novel subdivision driving technology for brushless DC motor. Firstly, on-line brushless DC motor commissioning and configuration platform is set up based on FAULHABER drive systems with Motion Controllers, which is applied to realize subdivision simulation and to determine reasonable subdivision parameters. Secondly, experimental circuit for brushless DC motor driving and controlling is designed and printed. Lastly, the simulated subdivision parameters are verified by debugging the new driving board. Experiments indicate that the proposed brushless DC motor subdivision algorithm can achieve the expected functions, and moreover, power consumption and heating of the new driving board are observably decreased by the circuit layout optimization and the chip selection. Strikingly, the area of the new driving board is reduced by 36% than the former one. The brushless DC motors driven by subdivision technology keep the advantages of stepper motors such as high positioning precision and stability in low-frequency range, while overcome the disadvantages mentioned above. Thus, an innovational optical fiber positioning unit based on brushless DC motor is developed with high precision and reliability in this paper.

9912-183, Session P6

Pupil slicer design for the NASA-NSF extreme precision Doppler spectrograph concept "wisdom"

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The formula describing the resolution (R) of a spectrograph clearly shows that maintaining a constant R value requires the collimated beam diameter, and thus the size of the instrument, to scale linearly with telescope diameter. This scaling relation becomes increasingly problematic for high-resolution echelle spectrographs, since the beam size is also proportional to R. Thus Precision Radial Velocity (PRV) instruments with R>100k require large gratings and optics, driving the cost and complexity of such spectrographs designed for large telescopes. Implementation of PRV instruments on the next generation of extremely large telescopes therefore calls for extreme budgets – or some clever solutions to keep the instrument size at bay, without sacrificing throughput.

Image or pupil slicing is one such solution, employed most recently in the G-CLEF design for the 25m aperture of the GMT. While a 3.5m telescope diameter allows for conventional approaches, as demonstrated by the HARPS instruments, the use of pupil slicing is still beneficial in reducing the overall size of the instrument. For our design of the "WISDOM" (WIYN Spectrograph for DOppler Monitoring) instrument concept, a response to the NASA-NSF call for a ground-based support facility of the Transiting Exoplanet Survey Satellite (TESS), we had to turn to this solution as the observatory could only offer a limited space for the installation of the instrument.

The primary of the telescope is conjugated to a small, 75mm diameter parabolic mirror, which is physically cut into six triangular segments that are slightly pushed in radially. These mirror segments feed light into six individual fibers, each with a core diameter of 32 microns. As this unit has to be mounted directly on the folded Cassegrain port of the WIYN telescope the challenge is not just to achieve but also to maintain the alignment of the optics in the changing gravitational and varying thermal environment. Since the fibers are very small and densely packed we chose to align the mirrors rather than the fibers. The "pizza-slice" shaped mirror segments are kinematically mounted by cantilevered tabs that are bonded to the outer edge of each segment. After initial alignment precision shims are ground to the measured thicknesses to permanently set the positioning. To mitigate the thermal changes we employ low thermal expansion materials: zerodur for the mirrors, invar and carbon fiber for the structure. To avoid misalignments induced by changing gravitational load the fibers are supported by a very stiff carbon fiber hexapod structure. FEA analysis aided the optimization of the support struts and spider vane structure to achieve <3 micron misalignment for the expected working conditions.

9912-184, Session P6

Slitmask based pupil scrambling integral field unit for the Robert Stobie spectrograph on SALT

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We propose to build an integral field unit (IFU) for the Robert Stobie Spectrograph (RSS) on the Southern African Large Telescope (SALT). The Pupil Scrambling IFU (PSI) will employ the scrambling properties of fibers to address fundamental problems in achieving photon-limited sky subtraction due to variations in pupil illumination during observations. PSI will be fully encapsulated with a compact folding scheme in a standard longslit mask—far thinner than any previous fiber-based implementation.

The IFU will cover 14 x 24 arcsec on sky, achieving spectral resolution R ? ?/?? up to 6200 and photon-limited sky subtraction for studies of faint extended gas around galaxies beyond the reach of current 4m-class instruments. It will incorporate new-technology octagonal shaped fiber cores coupled by telecentric, pupil-imaging lenslets to fully optimize pupil scrambling and provide 100% integral sky coverage. The PSI design consists of 300 microlens-coupled octagonal fibers, delivers fully integral-field coverage over a 14 arcsec x 24 arcsec field, performs well over the full bandpass from 350 nm to 900 nm, and achieves spectral resolution up to R=6200. The IFU contains 274 fibers in an elongated hexagon. There are 26 sky fibers in two mini-slits.

The PSI will require no modifications to the existing RSS instrument, as it is inserted like a longslit mask by the existing mechanism. Light from the telescope is picked off by fold prisms just before the telescope focal plane and sent through MLAs bonded to the prisms and mechanically aligned to the IFU head and sky fiber mini-slits. Fibers wrap around inside the cartridge with ample radius of curvature to V-groove blocks, output

microlens arrays, and fold prisms that are configured into a spectrograph entrance pseudo-slit. Sky fibers will be placed at the ends of every V-groove block in the spectrograph slit. The spectrograph slit, mini-slit (sky), and IFU are all folded by prisms that are optimized with AR coatings. Microlens arrays are bonded to the prisms and aligned as an assembly to the fibers via the flexure mounts.

This paper will show results of simulations and measurements done on the fiber scrambling properties of hexagonal fibers. It will also provide details of the optical and mechanical design of this Slitmask - based IFU.

9912-185, Session P6

Characterizing octagonal and rectangular fibers for MAROON-X

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We report on the scrambling performance and focal-ratio-degradation (FRD) of various octagonal, rectangular, and square fibers considered for MAROON-X, a new fiber-fed, red-optical, high-precision radial-velocity spectrograph for the 6.5m Magellan Telescope in Chile. Our report demonstrates the influence of different cladding types and shapes around rectangular fibers on their FRD behavior. We also discuss the difference in FRD between bare and connectorized fibers.

9912-186, Session P6

Modern fiber manufacturing and testing

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Optical fibers have been widely used in astronomical instruments for decades. The basic properties of fibers and their manufacturing processes have not really changed much, although several recent applications have called for custom solutions. These include development of special core geometries, tailoring of refractive index values/profile, tight control of primary properties (e.g. core diameter, transmission) and understanding of secondary properties like focal ratio degradation (FRD). Customization and specification of tight tolerances come at a price, and without an insight into the manufacturing process it is hard for the end users to gauge what is feasible and where to draw the line in a trade study. Also, sensitive post-manufacturing tests (for FRD, transmission), or post-processing (tapering, splicing) requires expensive instruments and the results can highly vary from group to group. Therefore this paper provides details on current production, post-processing and recently developed testing capabilities, from the manufacturer point of view but with the astronomer in mind. With over 30 years of experience Polymicro Technologies has been in the forefront of the optical fiber industry, and even though astronomy is not a truly profitable application area, Polymicro has been taking pride in fulfilling the desires of the astronomical community.

9912-187, Session P6

A new miniaturized wireless driving system for LAMOST fiber positioning

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The fiber positioning system is one of the most important parts of LAMOST (The Large Sky Area Multi-Object Fiber Spectroscopic Telescope), which consists of 4,000 fiber positioning nodes and each of them can position a fiber. In addition, all of the fiber positioning nodes are distributed on the focal plate of 1.75m in diameter.

As the self-innovation and key technology of LAMOST, the fiber positioning system has been working steadily for more than 6 years. At present, a higher demand to install at least 5,000 fiber positioning nodes on focal plate of 1.75m in diameter is put forward and the most effective solution is to miniaturize the fiber positioning nodes. Every fiber positioning node consists of three parts: the wireless driving system, the mechanical device and the two stepper motors. The size of stepper motor has reduced from 10mm to 6mm in diameter, but the size of mechanical device depends on the wireless drive system. Therefore, to miniaturize the wireless driving system is of great importance and difficulties as well.

The previous wireless driving system board is 100 mm long and 15 mm wide and consists of the minimum system of wireless SOC based on technology of ZigBee wireless communication and the stepper motor driver module. In order to miniaturize the wireless driving system, two steps are proposed in the paper. The first step is to separate the whole wireless driving board into two parts of the minimum system board of wireless SOC (30mm x10mm) and the stepper motor driver module (8mm x 8mm). Compared with the pre-board installed at the end of the fiber positioning node, the new minimum system board of wireless SOC is installed at the end of fiber positioning node and the stepper motor driver module is installed at the end of the stepper motor. The second step is to adopt a smaller-size wireless SOC to replace the original one. The CC2530 used on new board is 6mm long and 6mm wide as a true system-on-chip solution for IEEE 802.15.4 and ZigBee applications launched by TI. The previous MC13213, with the size of 9mm x 9mm, possesses less performance of MCU and peripherals.

As a result, the size of the new wireless driving system reduces by above 60%. Meanwhile, the entire structure of every fiber positioning node can be designed smaller. Finally, more than 5,000 fiber positioning nodes with an alveolate distribution can be installed on the focal plate of 1.75m in diameter, of which the dense increases by 20%.

9912-188, Session P6

A new modular guidance system for the Southern African Large Telescope

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Following successful commissioning of the guidance probe on the Southern African Large Telescope (SALT) Fiber Instrument Feed (FIF), the concept was developed further in a project to re-design the guidance system currently supporting Robert Stobie Spectrograph (RSS) observations. The features of the new system, its mechanical and optical designs and its control system architecture are presented. Improvements to the operational user interfaces and integration of the new RSS probe with the greater SALT software control system are also discussed.

The systems engineering approach was taken allowing the core science and operational requirements to drive the re-design from the ground up.

Lessons learnt from the first two years of FIF probe operations and how they influenced the new design are presented. Newly adopted project management and design processes were used to good effect to streamline and monitor all aspects of the project. Major features of the new system include a compact, modular and removable design, high optical efficiency, a double-probe positioning system enabling both translation and rotation guidance corrections as well as optional closed-loop focus feedback.

A strong requirement for maintainability and advances in technology allowed a new control system architecture to be employed, resulting in the first line-replaceable guidance subsystem at SALT. The electronic control system is housed in an easily accessible cooled enclosure, while the positioning mechanics, optics and detectors form a removable unit mounted directly to the instrument.

A double-probe rectilinear positioning mechanism using off-the-shelf linear translation stages was developed that allows accurate selection and simultaneous imaging of two guide stars enabling telescope de-rotation guidance corrections — especially important during long-exposure multi-object-spectroscopy (MOS) observations. The mechanical design provides significantly faster guide star acquisition times as well as accurate offsets while closed-loop guidance is active to precisely re-position science targets within the telescope field of view during an observation.

Compared to the existing RSS probe, the optical train and camera system employed on the FIF probe improved sensitivity by a factor of eight, allowing successful guidance on much fainter objects — up to 20th magnitude in the V band. This optical design was extended to include a deployable two-face pyramid wavefront sensor that enables focus-sensing functionality while retaining throughput efficiency. Some caveats and characteristics of this wavefront sensing method are discussed.

Motion control is accomplished via a compact re-configurable input/output (cRIO) embedded controller from National Instruments. Each motion stage is driven by a stepper motor and provides accurate position feedback via linear optical grating encoders. The embedded controller also hosts the guidance image processing functionality and high-level software control system that interfaces to the rest of the telescope control system (TCS) via middleware based on the Data Distribution Service (DDS) standard.

9912-189, Session P6

Design, development, and performance of the fibers of MOONS

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The Multi-Object Optical and near-Infrared Spectrograph (MOONS) will exploit the full 500 square arcmin field of view offered by the Nasmyth focus of the Very Large Telescope and will be equipped with two identical triple arm cryogenic spectrographs covering the wavelength range 0.64μm-1.8μm, with a multiplex capability of over 1000 fibres. Each spectrograph will produce spectra for 500 targets simultaneously, each with its own dedicated sky fibre for optimal sky subtraction. The system will have both a medium resolution (R~4000-6000) mode and a high resolution (R~20000) mode.

The fibres are used to pick off each sub field of 1" and are used to transport the light from the instrument focal plane to the two spectrographs. Each fibre has a microlens to focus the beam into the fibre at a relative fast focal ratio of F/3.7 to reduce the Focal Ratio Degradation (FRD).

This paper presents the design of the fibre management module and describes the specific developments required to optimise its performances.

9912-190, Session P6

PEPSI-feed: Linking PEPSI to the Vatican-Advanced-Technology Telescope using a 450m long fiber

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Limited observing time at large telescopes equipped with the most powerful spectrographs, makes it almost impossible to gain long and dense time-series of observations. Ditto, high-time-resolution observations of bright targets with high signal-to-noise are not always possible with large telescopes. By pulling an optical fibre of 450 m in length from the Vatican-Advanced-Technology-Telescope (VATT) to the Large-Binocular-Telescope (LBT) to connect the Potsdam-Echelle-Polarimetric and Spectroscopic Instrument (PEPSI), allows to gain from the advantages of ultra-high resolution measurements on bright targets. This article presents the fibre-link in detail from the technical point-of-view as well as future plans and will also demonstrate it's performance by first observations.

9912-191, Session P6

Design of multi-motor distributed control system for optical fibers positioning based on CAN bus

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In fiber spectroscopic telescopes, the real-time precise position measurement of the optical fibers is the key to track the stellar objects .CAN bus is a bus-based serial communication network which can support distributed control or real-time control effectively. As a kind of industry fieldbus, it is widely used among industry circle because of its outstanding reliability, real time and flexibility.

In the fiber positioning system, every fiber positioning node is driven by two stepping motors. According to the general structure of distributed control system, an overall scenario for multi-motor distributed control system based on CAN bus is given. Taking the integration CAN control chip as main controller, the hardware of CAN intelligent node and adapter is designed to be the bottom hardware platform for the whole system. Following the performance features and the technical specifications of CAN bus, the application layer protocol of CAN bus is set down on the basis of soft model for the intelligent node, including the assignment of message identifiers, the design of frame format, the method of data exchange and the mechanism of message filter. Besides, some software interfaces are designed, such as message sending and receiving, motor control and so on; the main function flow charts for intelligent node and adapter are given and the software designed for intelligent node and adapter is completed.

9912-192, Session P6

Optimal non-circular fiber geometries for image scrambling in high-resolution spectrographs

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Optical fibers are a key component for high-resolution spectrographs to attain high precision in radial velocity measurements. We present a custom fiber with a novel core geometry - a 'D'-shape.

From a theoretical standpoint, such a fiber should provide superior scrambling and modal noise mitigation since, unlike the commonly used circular and polygonal fiber cross sections, it shows chaotic scrambling. This difference is demonstrated by simulations. We report on the fabrication process of the test fiber, and compare the optical properties, scrambling performance and focal ratio degradation of the D-fiber with those of common polygonal fibers.

9912-193, Session P6

High numerical aperture multimode fibers for prime focus use

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Modern 8-10m class telescopes have prime focus speeds too fast for direct use with normal silica-cored fibers, which are limited to ~f/2.5. Specifically, the current design for the proposed Mauna Kea Spectroscopic Explorer telescope is f/1.97 . Micro-fore optics can be used to slow the beam, as for PFS on Subaru, but this adds cost, complexity and losses. A simpler alternative is offered by high Numerical Aperture (but still purely silica-cored) fibers, which are now available from multiple vendors. The results of throughput and focal ratio degradation (FRD) tests on two samples of these high NA fiber are presented, and also on normal NA fiber with identical other properties, for comparison. It is found that high NA fibers exhibit acceptable performance, but that all fibers suffer a progressive loss of throughput as the NA is approached.

FRD is caused by the light scattering in the fiber, micro-bend of fiber from the stress and the imperfection quality of the fiber end face. The glue between the cladding and ferrule, the ferrule diameter and the length of fiber all can influence the FRD performance of the fiber. In this paper, we investigated the FRD performance with different glues, ferrule sizes and fiber length conditions. It is also investigated the near field centroid movement at the output of fiber when the input beam is varied and moved across the input fiber core.

The experiment results are reported about the FRD performance of high NA fiber for MSE. The high NA fibers are obtained from both Polymicro Inc. and CeramOptec Inc. To test the FRD at different spatial frequency, the collimated beam is injected to the fiber at different angle. The far field distribution obtained by the CCD camera is a ring of different thickness at different input angle. There are two peaks for the beam profile across the ring center, and the half distance between the peaks is the incidence angle of the input collimated beam. The FWHM of the ring is the measured FRD, which is the angle increment of the output beam. By changing the glues, ferrule size and the length, we investigated how those variables influence the FRD performance for different input beam angle.

During the operation of the telescope, the input at the fiber is a converging beam. Hence, to simulate and test the real situation for the telescope working conditions of these fibers, we also use the converging beam to test the FRD performance for the high NA fiber. The point source microscope is used to generate the optical beam of different NA. For each NA, we take a series of images of the far field disk of the output beam at different positions. By calculating the diameter of 90% encircled energy of a series beam, we can precisely measure the output NA. By using different objective lens with the point source microscope, the FRD performance is also investigated.

The near field performance of high NA fibers is also investigated. It is found that there is no significant movement of the output near-field centroid when the fiber input angle is varied and the input beam moves across the input fiber core.

9912-267, Session P6

A 24mm diameter fibre positioner for spectroscopic surveys

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Since the beginning of the last century, Einstein's theory of general relativity has shaped our understanding of the evo-lution of the universe. Using the equations of Friedman-Lemaître and the data of many astronomical surveys, the model predicts that the expansion of the universe is slowing down asymptotically to zero due to the gravitational force between the matter. In 1998, the observation of 42 type Ia Supernovae has revolutionized our understanding of the history of the universe. The generally accepted view of a flat universe was proven wrong. The measurements show that the expansion of the universe is not slowing down but accelerating. In order to unify the theory of general relativity and the measured acceleration of the expansion of the universe, an additional term was added to the equation: Dark Ener-gy.

This revolution has motivated a lot of researchers of fundamental physics and astrophysics to confirm the accelerating expansion and to measure it precisely throughout the history of the universe using different techniques.

Ten years ago, observation of the spatial distribution of galaxies, allowed to develop a new technique for measuring the expansion of the universe: the measurement of baryonic acoustic oscillations.

The key is to measure the 3D position of a multitude of galaxies: about 30 million. As of today, we know the exact 3D position of only ~3 million galaxies. The last million was measured during the last 3 years. At this rate the goal of 30 million will be obtained at the end of this century.

In order to measure a high number of galaxies in a practical amount of time, we need to observe multiple objects in parallel. Instead of a mounting a spectrograph directly, thousands of optical fibres are placed in the focal plane of a telescope. Each fibre is positioned in the focal plane such that it gathers the light of a certain object and transmits it to a spectrograph. In this way each fibre represents a moving pixel and almost all the fibres can transmit science infor-mation and the spectrograph is used more efficiently.

Each fibre has to be positioned to several μm precision in the focal plane of a telescope for each exposure. Each fibre is positioned by a 2-axis fibre positioner. In this paper we present such a fibre positioner with 24-mm diameter and driven by two brushless DC motors in combination with a backlash free gearbox. 1000 positioners can be fitted in a ~800-mm diameter focal plane. The positioner has an optimal central fibre path and improved angular alignment. In fact, the fi-bre runs through the centre of the positioner and is only bent at the top in order to reach its target position. In this way, the flexion and torsion of the fibre is minimal. In addition to the very high positioning accuracy, the design is optimized to allow a minimal tilt error of the fibre. This is demonstrated using a novel optical tilt measurement system.

9912-194, Session P7

MEGARA: high-precision alignment system for gluing fibers and microlenses

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MEGARA (Multi Espectrógrafo en GTC de Alta Resolución para Astronomía) is the future optical Integral-Field Unit (IFU) and Multi-Object Spectrograph (MOS) for the 10.4-m Gran Telescopio CANARIAS (GTC). MEGARA will offer two different observing modes, the Large Compact Bundle (LCB) mode, an Integral Field Unit (IFU) composed by 567 fibers covering 12.5" x 11.3" on the sky and a Multi-Object Spectroscopy (MOS) mode that will allow observing 92 objects in a region of 3.5' x 3.5' around the LCB IFU. The MOS mode is composed of the robotic positioners carrying a minibundle of 7 fibers that covers a circular area of 1.6" diameter on the sky. Eight mini-bundles will observe sky during the observations with the LCB for calibration purpose.

The MEGARA focal plane subsystems will be located at the GTC Folded Cassegrain F (FC-F) focal station. The MEGARA optical components at the focal station are a field lens to provide telecentricity correction, the micro-lenses arrays to couple the telescope beam to the collimator focal ratio at the entrance of the fibers and the fiber bundles, to conduct the light from the FC-F to the pseudo-slit plates at the MEGARA spectrograph, placed at Nasmyth–A platform.

The microlens arrays shall define the FOV to be introduced in the fibers, adapting F# from f/17 (GTC telescope) to f/3 (Fibers) to minimize FRD and to provide a telescope pupil image on the 100?m fiber core. The spaxel size is 0.62 arcsec oversizing the pupil image and finding a compromise to optimize the following parameters: a) the flux recovered from point sources with each MEGARA MOS mini-bundle, b) the fraction of lost light when reimaging the pupil on the fiber core, c) the need of fully imaging the fiber core in order to preserve the quality of the fiber-to-fiber relative-flux calibration and d) the differential atmospheric refraction effects that has to be minimized.

The fraction of pupil imaged shall have a variation less than 10% from fiber to fiber. This requirement yields a 10 ?m tolerance for positioning the pupil image on the fiber core.

A detailed error budget was prepared for deriving the manufacturing tolerances of the frames supporting the fibers, the microlens diameters and positions at the array, the external fiber diameters, the positioning accuracy of the robotic positioner and, the performance of the gluing system between fiber and microlens, which must achieve a centering precision better than 5μm.

This article gives an overview of the MEGARA Fiber Bundles and presents the gluing system between fibers and microlens arrays developed for the MEGARA project to provide the alignment precision and the resulted performance measured during the real integration and verification phase.

9912-195, Session P7

Shock and vibration testing of digital micromirror devices (DMDs) for space-based applications

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One of the key goals of NASA's astrophysics program is to answer the question: How did galaxies evolve into the spirals and elliptical galaxies that we see today? A space mission concept called Galaxy Evolution Spectroscopic Explorer (GESE) was developed to address this question by making a large spectroscopic survey of galaxies at redshift z~1-2 (8-10 billion years lookback). A multi-object spectrometer based on a digital micromirror device (DMD) was designed for this mission. A DMD is an array of micromirrors which can be addressed individually and tilted into one of two states (+/- 12° w.r.t. the device plane), which makes it a very versatile binary light modulator. A Texas Instruments Cinema DMD (with approximately 2,000 rows of pixels in the cross-dispersion direction) can be used to obtain spectra from hundreds of point sources, simultaneously. GESE is designed to obtain spectra of approximately 100 galaxies per exposure (which is the number of galaxies in the field of view, bright enough to achieve S/N = 6, or better). Recently, the use of DMDs for ground-based multi-object spectrometers (MOS) has been demonstrated. The compact size and small weight of DMDs makes them especially attractive for a space-based MOS, where the only current alternative is an array of microshutters. DMDs were originally designed for visible range applications; therefore the protective glass window they are supplied with does not have sufficient throughput in the UV and has to be replaced. As part of a larger effort to investigate the use of DMDs in space telescopes (sponsored by a NASA Strategic Astrophysics Technologies grant), we developed a procedure to replace the DMD window and performed vibration and shock testing on Texas Instruments DMDs. In this work, we describe the procedure by which we replaced the standard window with UV-grade fused silica, sapphire and magnesium fluoride. We performed initial shock and vibrational tests to evaluate the mechanical robustness of the re-windowed devices to investigate the ability of these devices to survive the expected vibrational and shock loads endured in the launch phase (using typical parameters for a Falcon 9 launch). Furthermore, we performed residual gas analysis to study the outgassing properties of the new DMDs and evaluate the ability of the new seals to protect the device.

9912-196, Session P7

Development of an optical device "Field Stacker" for achieving accurate photometry in ground-based mid-infrared observations

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Time-variation in atmospheric transmittance is a serious problem in ground-based mid-infrared observations. It degrades photometric accuracy and makes monitoring observations difficult. To improve the photometric accuracy, science and calibration objects should be observed simultaneously to compensate the time-variation in atmospheric transmittance. However such kind of observations cannot be practically conducted since a field of view is small and a number-density of bright objects is low in mid-infrared wavelength range.

To overcome this problem, we have developed a new optical device, "Field Stacker". It is an optical system mounted just before the entrance window of the MIMIZUKU (Kamizuka et al. 2014), which is a mid-infrared instrument for the TAO 6.5-m telescope (Yoshii et al. 2014). The Field Stacker is composed of two pick-up mirrors, one combining mirror, and three types

of moving stages (tilt stages, linear stages, and rotating stages). All components are placed at room temperature. The pick-up mirrors are moved by the moving stages and fetch two arbitrary fields from the TAO 6.5-m telescope's wide FoV (25 arc-minutes in diameter). The two fields are merged by the combining mirror and focused onto a single detector. By observing science and calibration objects simultaneously, the MIMIZUKU equipped with the Field Stacker will enable mid-infrared observations with a high photometric accuracy based on real-time calibration.

A requirement of photometric accuracy for achieving our science goals is 1%. There are two important points to be concerned. The first one is the position accuracy of the pick-up mirrors. The error in the angle of the pick-up mirror affects the system throughput. Since the photometric accuracy depends on the throughput ratio between the two fields, the tilt error degrades the photometric accuracy. Tilt errors are caused by the tilt stages and the linear stages. We measured tilt errors of each stage and confirmed that the tilt errors are small sufficiently to achieve the requirement. The second one is spatial variation in atmospheric transmittance. Since the spatial distribution of atmospheric transmittance in arc-minute scale is not well understood, we estimated the fine arc-minute scale spatial variation in atmospheric transmittance by analyzing a mid-infrared background flux variation, which traces the variation in the atmospheric transmittance. The flux data were taken by the MAX38, which is a mid-infrared instrument for the miniTAO 1-m telescope located in the same site as the TAO 6.5-m telescope.

In addition, we prepare a list of the calibration sources available for the Field Stacker and estimate the sky coverage where the Field Stacker functions successfully. Red super giants are good candidates for the calibration sources because normal stars are too faint in the mid-infrared. Red super giants are enough bright for ground-based mid-infrared instruments, and flux variability in red super giants is sufficiently small. We are investigating the distribution of the calibration sources using infrared all sky catalogs (AKARI, WISE, etc.).

The Field Stacker will be put to practical use by the MIMIZUKU which is commissioned in 2016. In this paper, the current development status of the Field Stacker will be presented.

9912-197, Session P7

Multi-resolution waveguide image slicer for the PEPSI instrument

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A waveguide image slicer for the LBT's PEPSI instrument was successfully developed and tested. It comprises of three different slicers that serve for the theoretical 43k, 120k and 270k resolutions of the spectrograph, incorporating in between 7x 70μm, 5x 175μm and 3x 500μm single waveguides that couple light from the telescope fibers (100 μm, 200 μm and 300 μm core), slice the images and re-project them into the slit of the spectrograph. Each type of slicer is manufactured from thin glass sheets of the respective thickness that are bonded together by an index matching adhesive (n=1.42) that serves for total internal reflection within the thin glass of D263T (n=1.5233) when coupling into it using the NA of the telescope fibers. The adhesive bonding layer is kept at a minimum of ca. 3..4μm between every thin glass slice to allow for a highest filling ration of waveguiding structures within the cross section of the slicer. The quadratic and best fiber diameter matching cross sections of the bonded waveguide stacks are realized by precision micromachining using grinding and polishing, total internal reflection then is also realized at the sides of the thin glass waveguides by bonding cover plates there using the same index matching adhesive. Anti-reflection coatings on windows at the entrance and the output of the image-slicers are used for minimal losses, the throughput of each image-slicer is ca. 92%. All image-slicers are integrated on one common substrate, allowing for an easy handling of this highly complex and miniaturized optical unit during alignment within the spectrograph.

Each individual waveguide slice is of different length, the distal end is polished under an angle of 45° and coated with protected silver. Thus, light exits the slicer at an angle of 90° with respect to the fiber entrance and with a spatial offset pitch of the sliced light. Because all three resolution modes are filling the slit CCD to a full extent, the slicer stack separation for all fiber cores in the focal plane of the collimator are the same. The ultra high resolution mode is using the smallest of the three fiber cores, the 100 μm fiber with a 0.74?? entrance aperture on the sky. It is sliced 7 times, reaching the practical limit due to the available space on the CCD detector.

9912-198, Session P7

Opto-mechanical design of an image slicer for the GRIS spectrograph at GREGOR

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GRIS is the spectrograph installed at the 1.5m Ø GREGOR telescope. It was initially designed to operate in a standard long-slit configuration together with the TIP polarimeter for high-spatial high-sensitivity spectropolarimetric observations. As a part of the SOLARNET project, an image slicer has been recently designed to make possible the simultaneous measurement of all points in a 2D field of view, as a prototype of the MuSICa integral field unit for the European Solar Telescope.

The general approach to upgrade GRIS consists in making removable the upper part of the instrument (which includes the long slit, the polarimeter and a folding mirror that sends the light to the floor below in the building, where the collimator and camera mirrors of the spectrograph are located) by mounting it on a removable bench called "SLIT bench" and inserting in its place the "IFU (Integral Field Unit) bench" for the 2D mode. Special tight requirements were derived from the small free room available at the spectrograph entrance to locate all the necessary optical and mechanical elements.

The IFU is composed of a slicer block, an array of collimator mirrors and an array of camera mirrors. With this optical setup, an input 2D field of view of 6.75" x 3" of the solar image will be cut and aligned to produce a single slit of 54" x 0.375" at the entrance of the spectrograph GRIS. This subsystem is currently being manufactured by Winlight optics, within the framework of the SOLARNET project. A specific mount for the IFU has been designed to ensure thermal stability and keep its nominal. Rotation adjustments around three axis are adjusted separately with a resolution better than 50". The rotation point is placed at the center of the IFU output slit, with a displacement error less than 20 microns.

A field-of-view scanning system has been designed to make possible the illumination of the IFU by different parts of the solar image produced by the telescope. This field-of-view scanning system is coupled to the IFU by means of an appropriate reimaging subsystem, composed of two identical spherical mirrors, RS1 and RS2. While scanning, the light beam goes towards RS1 with an error under 5 microns in position and 50" in angle. The distance between the entrance window and RS1 is constant to keep the system in focus, independently of the entrance window position.

To optimize mounting/dismounting and alignment operations, the long-slit and IFU configurations are based on two different interchangeable

plates positioned through kinematic contacts fixed on the main GREGOR instrument bench. Both plates will be integrated and aligned separately, firstly in laboratory and finally at GREGOR in real conditions.

This paper describes the opto-mechanical IFU bench and all the optical and mechanical components that lie on it, which will permit to validate the image slicer concept for 2D solar spectropolarimetry of EST.

9912-199, Session P7

Performance estimates for spectrographs using photonic reformatters

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As the demands for stability and precision placed upon high resolution spectrographs increase, instrument designers are forced to make improvements and address errors in new areas. One such area is modal noise, which occurs due to the changing spatial distribution of light at the output end of the fibre. This results in uncertainties in the positions of the resulting wavelength on the detector, and uncertainties in radial velocity measurements.

Modal noise becomes more of a problem as instruments move from the visible to the Near Infra-Red (NIR). This wavelength range is of particular interest to the astronomers, both to characterize stellar activity and search for planets around smaller cooler stars.

As the wavelength increases the number of modes within the science fibre decreases, increasing statistical uncertainties. In addition, laser frequency combs, the current state of the art stabilization method, are fed from a single mode fibre. When these are coupled into multimode fibres the modal pattern can vary, resulting in further errors.

The effects of modal noise can be mitigated using fibre scramblers, fibre agitators and different core geometries such as square and octagonal fibres. However, if these are not properly implemented they can still lead to incomplete scrambling, leaving residual uncertainties due to modal noise in radial velocity measurements.

A device that could remove conventional modal noise is a photonic reformatter. This device first uses a photonic lantern to sample the mulitmode PSF from a telescope. This light is then split into many individual modes, which are then reformatted using an Ultrafast laser inscribed chip.

Very similar in concept to a conventional image slicer, the resultant slit is single moded in one axis and multimoded in the other. By dispersing across the single moded axis and then summing the resultant spectra in the multimode axis, the uncertainties due to modal noise are removed, whilst retaining throughput.

This comes at a price however. Though the modal noise is removed, the reformatting of the modes can result in extra pixels being required to sample the spectra at the detector. In turn this will increase detector and read noise. Thus it is important to minimize the number of modes and know which regimes where using photonic instruments will result in higher signal to noise and hence stability than a conventional instrument.

To evaluate this, we will theoretically derive achievable radial velocity measurements to compare photonic instruments and conventional ones. Along with these results we will include ways of making photonic devices more competitive, by changing how the output spectra are sampled. We will discuss the theoretical and experimental investigations that will need to be undertaken to optimize and prove the photonic reformatting concept. We will also discuss the potential problems and solutions that may arise with the use of a photonic reformatter.

9912-201, Session P7

Collimating slicer for optical integral field units

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The development of a Collimating Slicer is to propose a new type of optical integral field unit which should be more compact. The main idea is to combine the image slicer with the collimator of the spectrograph. The traditional combination of slicer, pupil and slit elements and spectrograph collimator is replaced by a new one composed of a slicer and spectrograph collimator only. After testing few configurations, this new system looks very promising for low resolution spectrographs.

In this paper, the state of art of integral field units using image slicers will be described. The new system based onto the development of a Collimating Slicer for optical integral field units will be depicted. First system analysis results and future improvements will be discussed.

9912-202, Session P7

Spectral slicing for METIS: an efficient alternative to cross-dispersion

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Image slicing integral field units were developed to provide spatially resolved spectroscopy over a two dimensional field of view. Spectral slicing applies similar design principles to provide an alternative to cross-dispersion. A slicing mirror placed at the output from a low resolution spectrometer, or pre-disperser system, can be used to select specific spectral ranges within the overall spectrum. As in an image slicing IFU, these slices can then be reformatted to form an input slit for a high resolution spectrometer.

The key benefit over cross dispersion is the greatly increased flexibility in selecting wavelength ranges within the overall spectrum, and control over how these sub-bands are positioned on the detector, allowing a more efficient use of detector space.

We will describe the design of a deployable spectral slicing mode as part of the METIS LM-band high resolution spectrometer. In this system the spectral slicing mode can optionally be deployed to allow increased wavelength coverage at the expense of observing a smaller area on the sky.

9912-203, Session P7

A trial production of a large format image slicer unit for a possible future mid-infrared instrument on the TMT

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While the future space-based mid-infrared instruments will achieve the highest sensitivity and can target the faintest dusty structures extended more than several tens arcsec, a possible future mid-infrared instrument on the TMT with MIRAO opens up, for the first time, a new window to investigate the spectral variations among sub-arcsecond scale' structures of dust and gas in the mid-infrared. For example, Galactic nearby (< a few kpc) stellar sources of various stellar evolutionary stages and of various main sequence masses offer unique laboratories to investigate the life cycle of dust and gas in circumstellar environments. Those targets will be much more efficiently observed with the Integral Field Unit (IFU) spectroscopy having the FOV size of a few arcseconds by a few seconds rather than with the long slit spectroscopy having a few tens arcsecond's slit length. Facing on a growing demand of IFU spectroscopic capability in the mid-infrared for the TMT, we have carried out the trial production of large-format image slicer unit for the MICHI, a possible future TMT instrument, aiming to verify its technical feasibility. The key elements in our trial production are the monolithic large-format slice mirrors and the monolithic large-format pupil mirrors. The trial production piece of the monolithic large-format slice mirrors is designed to have 11 narrow mirrors (a thickness of 186μm), each of which has an angle offset between the neighboring mirrors by 2.4 degree against the incoming light. It has been produced from a single RSA6061 T6 aluminum block using ultra high-precision cutting machine with a single crystal diamond bite. The trial production piece of the monolithic large-format pupil mirrors is designed to have 11 spherical pupil mirrors and is produced from a single aluminum block. The results of our trial production of those key elements based on the ultra high-precision cutting techniques, the assembly of the large-format image slicer unit, the quality of pseudo slit image obtained by our trial production image slicer unit are described in this paper.

9912-268, Session P7

Measurements of the reflectance, contrast ratio, and scattering properties of digital micromirror devices (DMDs)

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Digital micromirror devices (DMDs) are micro-electro-mechanical systems, originally developed to display images in projector systems. A DMD in the focal plane of an imaging system can be used as a reprogrammable slit mask of a multi-object spectrometer (MOS) by tilting some of the mirrors towards the spectrometer and tilting the rest of the mirrors away, thereby rejecting the unwanted light (due to the background and foreground objects). A DMD-based MOS can generate new, arbitrary slit patterns in seconds, which significantly reduces the overhead time during astronomical observations. Critically, DMD-based slit masks are extremely lightweight, compact and mechanically robust, which makes them attractive for use in space-based telescopes. As part of a larger effort to investigate the use of DMDs in space telescopes (sponsored by a NASA Strategic Astrophysics Technologies grant), we characterized the optical performance of Texas Instruments DMDs to determine their suitability for use in multi-object spectrometers. The performance of a DMD-based MOS is significantly affected by its optical throughput (reflectance), contrast ratio (the ability of the DMD to reject unwanted light) and scattering properties (which could lead to crosstalk and reduced signal-to-noise ratio in the spectrometer). We measured and quantified the throughput and contrast ratio of a Texas Instruments DMD in several configurations (which emulate the operation of a typical DMD-based MOS) and investigated the scattering properties of the individual DMD mirrors. In this work we present the results of our analysis, describe the performance of a typical DMD-based MOS and discuss the practical limitations of these instruments (such as maximum density of sources and expected signal-to-noise ratio). This study is part of a new space mission concept, the Galaxy Evolution Spectroscopic Explorer (GESE), a multi-object spectroscopic survey in the ultraviolet (200 nm – 400 nm) regime.

9912-269, Session P7

Optical evaluation of digital micromirror devices (DMDs) with UV-grade fused silica, sapphire, magnesium fluoride windows and long-term reflectance of bare devices

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Digital micromirror devices (DMDs) are commercial micro-electro-mechanical systems, consisting of millions of mirrors which can be individually addressed and tilted into one of two states (+/- 12°). These devices were developed to create binary patterns in video projectors, in the visible range. Commercially available DMDs are hermetically sealed and extremely reliable. Recently, DMDs have been identified as an alternative to microshutter arrays for space-based multi-object spectrometers (MOS). Specifically, the MOS at the heart of the proposed Galactic Evolution Spectroscopic Explorer (GESE) uses the DMD as a reprogrammable slit mask. Unfortunately, the protective borosilicate windows limit the use of DMDs in the UV and IR regimes, where the glass has insufficient throughput. In this work, we present our efforts to replace standard DMD windows with custom windows made from UV-grade fused silica, UV-grade sapphire and magnesium fluoride. We present transmission measurements of the antireflection coated windows and the reflectance of the re-windowed DMDs. Furthermore, we investigated the long-term stability of the DMD reflectance, once the protective window has been removed.

9912-270, Session P7

Heavy-ion radiation testing of digital micromirror devices (DMDs)

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We present the results of heavy ion radiation testing of a digital micromirror device (DMD). A DMD is an array of micromirrors which can be addressed individually and positioned into one of two states, which makes the device a very versatile binary light modulator. DMDs are utilized in a variety of optical systems, especially projection systems. Recently, the use of DMDs for ground-based multi-object spectrometers (MOS) has been demonstrated. The compact size and small weight of DMDs makes them especially attractive for a space-based MOS, where the only current alternative is an array of micro shutters. As part of a larger effort

to investigate the use of DMDs in space telescopes (sponsored by a NASA Strategic Astrophysics Technologies grant), we performed radiation testing of Texas Instruments DMDs. Specifically, we investigated the suitability of DMDs for a new space mission concept, the Galaxy Evolution Spectroscopic Explorer (GESE). The orbit of the mission lies in deep space; therefore the DMDs used in the GESE MOS must be tolerant of cosmic rays. Earlier we presented the DMD's performance under accelerated proton radiation and in this work we present the results of accelerated heavy ion irradiation testing of the DMDs (with the control electronics shielded from radiation). Specifically, the testing focused on the detection of single-event effects (SEEs) including latch-up events. We present the results of testing with a range of different ions and calculated predictions for interplanetary space performance. In general, we found that DMDs are sensitive to non-destructive ion-induced state changes; however all SEEs were cleared with a soft reset (that is, sending a new pattern to the DMD). Our results suggest that an instrument exposed to background galactic cosmic rays in interplanetary space would experience a manageable single-event effect rate burden. During the testing the DMD did not experience single-event induced permanent damage or functional changes that required a hard reset (power cycle), even at high ion fluences.

9912-204, Session P8

How to achieve ultra-clean detectors and cryostats at astronomical instruments: measures to avoid contamination and dust at CCD detectors

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ESO (European Organisation for Astronomical Research in the Southern Hemisphere) developed in its detector laboratory a complete and comprehensive routine to achieve ultra-clean detectors with lasting effect which is given in detail in this paper: This is also a summary of ESOs achievements in this field over the last decades.

Only special suited materials are used for detector cryostats. After manufacturing they undergo some new surface treatments and processes and then are washed in ultrasonic baths with anti-corrosive soap or alcohol. After this all parts are baked to its maximum temperatures in very clean vacuum ovens. A final step would be the plasma cleaning of individual and also completely integrated and even closed detector vessel systems.

All handling and the complete integration is done in clean room environments of class 5

Before its integration the detectors are thoroughly inspected for particles and contaminations and If needed some new non-destructive methods e.g.: vapour cleaning are used for its removal.

Only after this the detectors are cooled down and operated. Then special routines of dust monitoring (pseudo FF dust counting, UV QE telescope on-side characterizations) can be taken as a contamination control over years. This is also added to the routine detector characterization beforehand in the head quarters laboratories..

The new approach is, that this final contamination control routine can be repeated after years of operation at the telescope site.

With all these in detail explained steps ultra-clean detectors are achieved which also do not degrade even after years of operation at the telescope sites.

After long years of experience ESO therefore guarantees to provide the astronomical community with very (long lasting) clean detectors at all its astronomical instruments.

9912-205, Session P8

The development of a cryogenic FTIR system for measuring very small attenuation coefficients of infrared material

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The high-resolution spectroscopy (?/?? > 20,000) in 2 – 20 ?m region is an important window for astrochemistry and astrobiology because we can access numerous ro-vibrational transitions of all kinds of molecules including those with zero permanent electronic dipole moment, which can never been observed in the radio region. However, it is technically difficult to realize high-resolution spectrographs for 30 m ground-based telescopes or space crafts because the spectrograph size becomes larger in proportion to the diameter of telescope for slit-limited spectroscopy or in proportion to the wavelength for diffraction-limited spectroscopy. Immersion grating can solve this issue by downsizing the spectrograph without any degradation of the spectral resolution. To realize a high-efficiency immersion grating for astronomy, the transmittance of material is essential because the typical optical path length in the immersion grating becomes greater than 100 mm, resulting in a significant degradation of the total efficiency even with a very small attenuation (the total energy loss of ~10% is expected for a Ge immersion grating with the attenuation coefficient of ?_att = 0.01 cm^-1 for the spectral resolution R = 100,000 at ? = 8 ?m). Therefore, we have started a project to quantitatively determine attenuation coefficients of various infrared materials applicable to immersion gratings with high-accuracy down to < 0.001 cm^-1. We have already reported the attenuation coefficients at the room temperature for the single-crystal Si, the single-crystal Ge, the CVD-ZnS, the CVD-ZnSe, and the high-resistivity single crystal CdZnTe (Ikeda et al. 2009 and Kaji et al. 2014). However, since the band gap and the edge of the lattice vibration band could slightly shift at the cryogenic temperatures, it is also inevitable to determine the attenuation coefficients at the cryogenic temperature for astronomical applications.

For these measurements, we developed a cryogenic FTIR system by adding a compact cryostat to the existing FTIR used for measuring transmittances at the room temperature. The volume of the cryostat is 315 mm (L) x 240 mm (W) x 270 mm (H), and the weight is about 28 kg including the cold-head of GM-cycle mechanical cooler. It is installed into the collimated beam of the FTIR system, and has two KBr entrance/exit windows with the clear aperture of 28 mm and the thickness of 8 mm. The samples can be cooled down to 20 K in this cryostat. Since we determine the accurate attenuation coefficient by comparing the transmittances between two samples made of same material with different thickness, they are required to be switched with good repeatability without any vacuum leak or temperature change. To meet with this requirement, we employ a linear-motion-feedthrough and a linear-motion-guide as a switcher of two samples. The linear-motion-guide can be stopped at fixed positions with a good repeatability by the grooved guide-wall that catches a roller plunger mounted on the side of the sample base plate. In this paper, we present the details of this cryogenic FTIR system, and report preliminary measurement results of some infrared materials under the cryogenic condition.

9912-206, Session P8

EUCLID near infrared spectro-photometer optical assembly (NI-OA) gluing interface ?qualification and gluing process development

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The Near Infrared Spectro-Photometer Optical Assembly (NI-OA) of EUCLID satellite project requires high-precision large lens holders with different lens materials. The aspherical-lenses are glued into their separate lens holder. The gluing of the lenses in their mounts with 2K-epoxy is selected as bonding process to minimize the stress in the lenses to achieve the required surface form error (SFE) performance (32nm) and lens position stability (±10μm) due to glue-shrinkage. Adhesive shrinkage stress occurs during the glue curing at room temperature and operation in cryogenic temperatures, which might overstress the lens, cause lens breakage or failure of the gluing interface.

The selection of the suitable glue and required bonding parameters, design and qualification of the gluing interface, development and verification of the gluing process was a great challenge because of the low TRL and heritage of the bonding technology. The different material combinations (CaF2 to SS316L and CuCr1Zr, LF5G15 and S-FTM16 to Titanium, SUPRASI3001 to Invar M93 and Nickel-Phosphor (NiP) coated Invar 36), large diameter (168mm) and thin edge of the lenses, cryogenic non-operational temperature (100K) and high-performance accuracy of the lenses were the main design driver of the development. The different coefficients of thermal expansion (CTE) between lens and lens mount produce large local mechanical stress. As hygroscopic crystal is calcium fluoride (CaF2) very sensitive to moisture, why an additional surface treatment of the gluing area is necessary.

Extensive tests e.g glue handling and single lap shear tests are performed to select the suitable adhesive. Interface connection tests are performed to verify the feasibility of selected design (double pad design), injection channel, the roughness and treatment of the metal and lens interfaces, glue thickness, glue pad diameter and the gluing process. CTE and dynamic measurements of the glue, thermal cycling, damp-heat, connection shear and tension tests with all material combinations at RT and 100K are carried out to qualify the gluing interface. The gluing interface of the glued lenses in their mounts is also qualified with thermal cycling, 3D coordinate measurements, Polarimetry and vibration test of the lens assemblies.

A multi-function double pad gluing tool and lens mounting tool is designed, manufactured and verified to meet the lens positioning and alignment performance of the lens in the holder which provides the possibility to glue lenses, filters, mirrors with different diameters, shapes and thickness with ±10μm accuracy in plane, out of plane and ±10 arcsec in tip/tilt with respect to the lens holder interface.

The paper presents the glue interface qualification results, the qualification/verification methods, the developed ground support equipment and the gluing process of the EUCLID high precision ?large cryogenic lens mounts. Test results achieved in the test campaign demonstrate the suitability of the selected adhesive, glue pad design, interface parameters and the processes for the precise gluing of the lenses in lens holders for all lenses. The developed process can also be used for other glass materials e.g. MaF2 and optical black coated metallic surfaces.

9912-207, Session P8

Final design of the Grism cryogenic mount for the Euclid-NISP mission

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The Euclid mission selected by ESA in the Cosmic Vision program is dedicated to understand dark energy and dark matter. One of the probes based on detection of Baryonic Acoustic Oscillations required the redshift measurement of millions of galaxies. This massive spectroscopic survey relies on the Near Infrared Spectro-Photometer (NISP) using grisms (for "grating prisms") allowing slitless spectroscopic mode. In this context, we designed a cryogenic mount for the four grisms which will be mounted together on a rotated wheel. This mount has to maintain optical performances and alignment at cryogenic temperature (130K) and to survive launch vibrations. Due to a very small mass and volume budget allowed to the Grism Wheel Assembly, our design relies on a weight relief Invar ring glued to the grism by tangential blades. Tangential blades have the advantage of small height but the drawback of less decoupling capabilities than bipods. First of all, we will present the final design of the grisms, and secondly the thermal and vibration tests (done in spring 2015) to successfully qualify the Grism Engineering Model in the Euclid space environment. In addition, the detailed Finite Element Analyses for the Flight Models will be presented, correlated to test results when possible, including random coupled analyses of the grisms on the complete wheel assembly and analysis of the impact of the interface preloads on the grism behavior.

9912-208, Session P8

CARMENES: NIR channel spectrograph cooling system AIV, thermo-mechanical performance of the instrument

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CARMENES is the new high-resolution high-stability spectrograph built for the 3.5m telescope at the Calar Alto Observatory (CAHA, Almería, Spain) by a consortium formed by German and Spanish institutions. This instrument is composed by two separated spectrographs, VIS channel (550-1050 nm) and NIR channel (900-1700 nm). The NIR-channel spectrograph's responsible is the Instituto de Astrofísica de Andalucía, IAA-CSIC. The channel has been manufactured, assembled, integrated and verified in the last two years. It was delivered to the observatory in fall 2015, and commissioned in December 2015. The expected performances comply with the scientific requirements and its science verification started.

One of the most challenging systems in the instrument involves the Cooling System of the NIR channel. Due to the highly demanding requirements applicable in terms of stability, the NIR Cooling System arises as one of the core systems to provide outstanding stability in cryogenic conditions (working temperature: 138K) to the NIR channel. Really at the edge of the state-of-the-art of the instrumentation so far applied to astrophysics, the CARMENES-NIR channel Cooling System is able to provide to the cold mass (1 Ton approx.) better thermal stability than few hundredths of degree within 24 hours, even achieving an astonishing goal of 0.01K per day.

The present paper describes the Assembly, Integration and Verification

phase (AIV) of the CARMENES-NIR channel Cooling System implemented at IAA-CSIC and later installation at CAHA 3.5m Telescope, where the CARMENES instrument is nowadays already running and producing valuable science. Relevant highlights are obviously shown in terms of real performance involving the key requirements requested to that system.

The CARMENES NIR-channel Cooling System has been implemented by the IAA-CSIC through very fruitful collaboration and involvement of the ESO (European Southern Observatory) cryo-vacuum department with Jean-Louis Lizon as its head and main collaborator. The present work sets an important trend in terms of cryogenic systems for future E-ELT (European Extremely Large Telescope) large-dimensioned instrumentation in astrophysics.

9912-209, Session P8

New cryogenic temperature monitor: PLT-HPT-32

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The PLT-HPT-32, a new cryogenic temperature monitor, has been developed by the Institute of Astrophysics of the Canary Islands (IAC) and an external engineering company (Sergio González Martín-Fernández).

The PLT-HPT-32 temperature monitor offers precision measurement in a wide range of cryogenic and higher-temperature applications with the ability to easily monitor up to 32 sensor channels. It provides better measurement performance in applications where researchers need to ensure accuracy and precision in their low cryogenic temperature monitoring.

9912-210, Session P8

GMTIFS: cryogenic rotary mechanisms for the GMT integral-field spectrograph

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The GMT Integral-Field Spectrograph (GMTIFS) is an infrared cryogenic instrument that combines both an Imager and an IFS. Both instruments are designed to operate with the Adaptive Optics System of the Giant Magellan Telescope. The instrument has eight mechanisms that have a rotational motion. The most stringent of these is the Science Selector which is a rotary mechanism with 5 positions that allow wavelength band selection between the Imager and the IFS. The IFS operates in reflection from the selected dichroic. As GMTIFS operates at the diffraction limit of the GMT, very small errors in the position of the reflected surface will lead to un-sensed errors in the IFS. The geometry of the optical design results in angular setting accuracy requirement of 0.34 arcseconds or 2.7x10-5 revolutions. This then requires a high dynamic range on the drive and position sensing systems. For the drive system this is achieved via a stepper motor and harmonic drive. For the position sensing we use a non-contact encoding technique. This technique uses eddy current sensors to sense the positional displacement of an eccentric target ring. As it is non-contact thermal issues are reduced and it is expected to be very reliable. The technique is also scalable to increase dynamic range with the addition of further sensors and target rings. This scalability is essential for the Science Selector. We present alternate versions of the technique adjusted for less stringent requirements. We provide a brief overview of the instruments different rotary mechanisms. We also present a variation of the position sensing technique applied to a linear mechanism. We report on the results of prototype testing of the eddy current sensors including cryogenic test results. This testing also includes cryogenic life testing of a harmonic drive and a bearing design.

9912-211, Session P8

Developing a long duration 3He fridge for the LSPE-SWIPE instrument

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The Large-Scale Polarization Explorer (LSPE) is a ballon-borne experiment aiming to detect the B-mode component of the polarisation of the cosmic microwave background. To achieve this, it will host two different instruments: STRIP (STRatospheric Italian Polarimeter) and SWIPE (Short Wavelength Instruments for Polarization Explorer). STRIP is based on coherent polarimeters and will observe the sky at frequencies below 100 GHz. SWIPE is based on TES (Transition Edge Sensor) detectors and will observe the sky at higher frequencies (140 GHz, 220 GHz and 240 GHz). The flight is foreseen for the the winter of 2016/2017 and will be launched from Svalbard Island. The experiment will last for at least 15 days, achieving sky coverage of almost 25%.

In order to maximize the observation time for the SWIPE instrument, we are developing a Helium-3 fridge that will be cycled only once during the flight, resulting in a cycle duration of more than 7 days. The LSPE-SWIPE fridge will be capable of keeping the focal plane arrays at temperature below 300 mK, considering a total heat load on the evaporator of 20 uW. This result is achieved by keeping the condenser of the fridge at a temperature of 1.5K, maintained by a bath of liquid Helium-4. The heat load on the evaporator is minimised thanks to an optimization of the length of the wires from the detectors at sub-K temperatures to the SQUID at 1.5 K, as well as the use of carbon fibre rods for structural support of the focal planes. The value of the heat load due to the thermal conduction from the 1.5 K condenser to the evaporator is only a small amount of the the total (4 uW is expected considering a tube of stainless steel 316NL).

The heat load through the tube is in principle not the lowest achievable; however, it is taken to be a reasonable compromise to keep the fridge compact. Indeed, in this way we have been able to design the tube from the condenser to the evaporator with a height of less than 50 mm. The total height of the fridge will be almost 300 mm, including the charcoal cryopump and the evaporator (designed to have a cylindrical shape of radius 6 cm). This geometry is chosen to minimize the Kapitza resistance, rendering it negligible in respect of the total heat load on the evaporator. To operate for >7 days with an expected heat load of 20 uW, the fridge will be charged with 0.61 moles of Helium-3, (corresponding to less than 14 L STP).

9912-212, Session P8

Sorption-cooled continuous miniature dilution refrigeration for astrophysical applications

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The search for B-mode polarisation anisotropies in the Cosmic Microwave Background is one of the primary preoccupations of modern cosmology. Detection would allow further constraining of cosmological parameters, as well as supporting the search for primordial gravitational waves and the testing of theoretical predictions of inflation. The next generation of telescopes to study the CMB will be based around bolometer arrays requiring sub-Kelvin operating temperatures. Furthermore, these ground-

based experiments will require longer hold times, greater temperature stability and accuracy, and extended operation in remote locations such as the Atacama Desert and Antarctica.

We report the latest progress on the development of a tiltable continuous miniature dilution refrigerator and associated 7-He sorption coolers being developed to meet the cryogenic requirements for several CMB experiments including POLARBEAR2, QUBIC and LSPE.

The twin-pumped recirculating diluter will provide cooling to 100 mK, with the condenser cooled continuously to 300 mK by two 7-He sorption coolers. The novel miniaturised system therefore benefits from a lack of external circulation pumps and a mechanically simple design (in particular the absence of cold moving parts).

The sorption pumps are operated by convective heat switches which also benefit from a lack of moving parts. The dilution unit features a thermally separated still, coil and step heat exchangers. The sorption coolers to provide 300 mK are combination 3He/4He fridges, where the 4He stage provides a 1 K pot to improve the condensation efficiency of the 3He stage. In order to optimise the sorption pump, extensive measurements have been made of the helium accumulation and pumping speed of a range of charcoal samples from a variety of sources and manufacturing processes.

9912-213, Session P8

CARMENES: NIR channel spectrograph, final design of an ultra-stable cooling system in the cryogenic range

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CARMENES is the new high-resolution high-stability spectrograph built for the 3.5m telescope at the Calar Alto Observatory (CAHA, Almería, Spain) by a consortium formed by German and Spanish institutions. This instrument is composed of two separated spectrographs: VIS channel (550-1050nm) and NIR channel (900-1700nm). The NIR-channel spectrograph is lead by the Instituto de Astrofísica de Andalucía, IAA-CSIC, and has been manufactured, assembled, integrated and verified in the last two years. It was delivered to the observatory in autumn 2015, and commissioned in December 2015. It has performed as expected, complying with the scientific requirements, and its science verification has begun.

Due to the highly demanding and difficult to attain long-term stability requirements of the high-accuracy radial-velocity measurements (?1 m s-1), an extremely robust cooling system using strategically positioned heat exchangers and fed with liquid nitrogen has been designed and integrated. The NIR channel of CARMENES has a working temperature of 138K and its cooling system is able to provide the cold mass housing the optics, of approximately 1 ton, with a thermal stability within 24 hours of a few hundredths of a degree, even achieving a goal of 0.01K per day.

The present paper describes the final design of the ultra-highly stable cooling system showing the mechanical assembly of the main parts and the components of the Cooling System hardware used to isolate in such an efficient way the instrument, which nowadays is running at the 3.5m telescope of CAHA.

The CARMENES NIR-channel Cooling System has been implemented by the IAA-CSIC through very fruitful collaboration and involvement of the ESO (European Southern Observatory) cryo-vacuum department with Jean-Louis Lizon as its head and main collaborator. The present work sets an important trend in terms of cryogenic systems for future E-ELT (European Extremely Large Telescope) large-dimensioned instrumentation in astrophysics.

9912-214, Session P9

Smart warping harnesses for active mirrors and stress polishing

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Active Optics is the art of controlling the deformations of optical surfaces. It is not only related to the stability of large primary mirrors, but has many applications as well as a control of the wavefront is required.

By working on the shape of mechanical structures constituting the warping harnesses of active systems, smart solutions appear, requiring the use of a single actuator to generate a combination of aberrations with a very high accuracy.

We successfully applied these optimization methods to provide an active mirror for the VLT-SPHERE planet finder, allowing to recover the dynamic of the extreme AO system. The active toric mirrors harness is designed to generate a pure cylinder or a pure astigmatism, compensating the deformable mirror residual shape due to its ageing.

We also reduced the number of actuators required for the stress polishing of ELTs segments. Smart structures allow a fine control of aberrations present in off axis parabolas surfaces, paving the way to a fast and simple mass production process.

We present both developments as well as the methods we successfully used for astronomical telescopes and instrumentation.

9912-215, Session P9

Control system for an alternative actuator for the primary surface of the large millimeter telescope (LMT/GTM)

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The Large Millimeter Telescope/Gran Telescopio Milimetrico (LMT/GTM), a 50m diameter millimeter-wave radio telescope situated on the summit of Sierra Negra, Puebla, at 4600 meters above sea level, is a bi-national project between Instituto Nacional de Astrofísica, Optica y Electronica in Mexico and University of Massachusetts Amherst in the USA. It is the world's largest, single dish, fully steerable, open air radio telescope designed for astronomical observations in millimeter wavelengths within 0.85 to 4mm. Its primary reflector is so massive that its shape deviates from the theoretical parabola due to gravitational effect as it moves in elevation. This deformation affects the gain, which is one of the most important features of a telescope, and one of the reasons why to build a radio telescope this big. To correct this elevation-dependent deformation, the primary reflector has been divided into 180 segments arranged in 5 concentric rings, with each segment being supported by 4 linear actuators with a range of motion of + 2mms. The segments in the three inner rings are currently being driven by an interim system that was reported in a previous SPIE paper. Unfortunately the lifetime expectancy is below the requirement and the cost of substituting the control electronics and mechanisms with the new actuators being developed for rings 4 and 5, may not be affordable. In this paper an alternative actuator control system is presented that uses most of the current electronics but uses a new motor and a completely redesigned mechanism. A companion paper is also presented regarding the mechanical changes. The results of the tests under positive and negative load are also presented, as well as the results on the performance; such as repeatability and accuracy, as well as the lessons learned when trying to compensate the large hysteresis found in the position sensor, a linear variable differential transformer (LVDT), that had not been reported in previous works. Preliminary data indicate that

this system is capable of achieving precision within plus minus 1 micron regardless of the size of the commanded step.

9912-216, Session P9

Thermal expansion as a precision actuator

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The UK ATC has developed a novel thermal actuator design as part of the OPTICON FP-7 funded project focusing on the production of freeform mirrors (FAME). The actuator uses the well understood concept of thermal expansion to generate the required force and displacement. As power is applied to the actuator it expands linearly with increasing temperature.

A resistance temperature detector (RTD) device is embedded into the centre of the actuator and is used both as a heater and a sensor. Electronics are used to control the temperature of the RTD by injecting a varying amount of current into the device whilst measuring the voltage across it. Temperature control of the RTD has been achieved to within 0.01°C.

This thermal actuator design, by means of a partly 3D printed actuator, is currently being used at the ATC to deform a mirror. This concept shows several advantages that makes it suitable to other applications. The actuator is cheap to produce whilst obtaining a high accuracy and repeatability. This actuator design would be suitable for applications requiring large numbers of actuators and high precision.

9912-217, Session P9

Realization and testing of an active mirror mechanism for in-field pointing in eLISA

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The Evolved Laser Interferometer Space Antenna (eLISA), foreseen to be launched in 2034, is meant to detect gravitational waves. It will consist of three spacecraft containing proof masses, mutually 5 million kilometers apart, which essentially forms a giant interferometer. The distance between the masses will be measured with extreme precision, so that any disturbance caused by a passing gravitational wave can be detected.

Since eLISA will be stationed in L1, the first Langrangian point of the Earth's orbit around the Sun, the spacecraft will orbit the Sun with the same (rotational) speed. As such, the spacecraft will be subject to seasonal constellation breathing, causing the angles between the interferometer arms to slowly change over a year. Consequently, the beams have to be corrected to stay aligned. One possible solution for this is to steer the line of sight of each telescope via rotation (over ±2.5°) of a single small mirror in an intermediate pupil plane of the telescope. To do so, an extremely accurate mirror mechanism needs to be developed, the so-called In Field Pointing Mechanism (IFPM).

TNO has made a conceptual design of such an IFPM, which has now been manufactured, assembled and subjected to a first set of tests. It consists of a mirror guided by a Haberland hinge, and actuated by walking piezosteppers. The steppers provide minuscule motion which, due to the stiff connection between the actuator and the mirror, allow precise rotation of the mirror. The exact motion profile of the steppers is determined by the voltage waveforms sent to their individual phases.

The performance of the IFPM has been assessed in a lab environment. Its response has been measured by both a nanometer resolution internal encoder, which is part of the IFPM itself, and an interferometer aimed at the mirror, providing nrad resolution direct measurements on the mirror rotation. This way the open loop motion of the mechanism has been optimized, by tuning the voltage profiles sent to the piezosteppers. The resulting frequency response functions, which vary slightly along the actuator stroke, have been measured, assessed and related to the observed open-loop motion in time domain. Based on these frequency responses a robust linear controller has been designed and implemented. This indeed yields a highly accurate closed-loop rotation of the mirror. The spectral density of the resulting closed-loop motion shows that the IFPM meets the extreme science mode requirements of 5 nrad/√Hz over the full ±2.5° while moving with 12.5 nrad/s. This is even true when the (coarser) internal encoder is used as feedback sensor, thanks to which the IFPM can be successfully operated in a stand-alone configuration (i.e. without external metrology).

9912-218, Session P9

Focal plane actuation by hexapod for the development of a high-resolution suborbital telescope

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We present a prototype hexapod image stabilization system as the enabling technology for a proposed suborbital balloon mission. The unique design thermally isolates an off-the-shelf non-cryogenic hexapod from the cryogenic focal plane enabling its use in a cryogenic environment. Balloon gondolas currently achieve 1-2 arcsecond pointing error, but cannot correct for unavoidable jitter movements (~50 microns at 20hz at the worst) caused by wind rushing over balloon surfaces, thermal variations, cryocoolers, and reaction wheels. The jitter causes image blur during exposures and limits the resolution of the system. Removal of this final jitter term decreases pointing error by an order of magnitude and allows for true diffraction-limited observation. Tip-tilt pointing systems have been used for these purposes in the past, but require additional optics and introduce multiple reflections. The hexapod system, rather, is compact and can be plugged into the focal point of nearly any configuration. For a 0.8m telescope the provided boost in resolution by this system would provide 0.1" angular resolution at 300nm, which is comparable to Hubble for a fraction of the cost. On an actual balloon, the hexapod system will actuate the focal plane to counteract the jitter using position information supplied by star-trackers. However, in the lab, we instead simulate such a mission, using a 1024 ? 1024 e2v science-grade CCD to take long exposures of a target attached to an X-Y stage driven with an actual suborbital balloon jitter signal (from the STO mission). Further confirmation of the positional accuracy and agility of the hexapod is achieved using a laser and fast-sampling position-sensitive diode. Endurance experiments were also carried out to determine the operational thermal and mechanical limitations of the system when operated for long periods. High-resolution time domain multispectral imaging of the gas giant outer planets, especially in the UV range, is of particular interest to the planetary community, and a suborbital telescope with the hexapod stabilization in place would provide a wealth of new data. On an Antarctic ~100-day Long-Duration-Balloon mission the continued high-resolution imaging of gas giant storm systems would provide cloud formation and evolution data second to only a Flagship orbiter.

9912-219, Session P9

Mechanical development of an alternative set of actuators for the outer rings of the LMT/GTM primary surface

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The Large Millimeter Telescope/Gran Telescopio Milimétrico (LMT/GTM) is a bi-national project between Mexico and the USA. It is the world's largest, single dish, fully steerable, open air radio telescope designed for astronomical observations in millimeter wavelengths within 0.85 to 4 mm. The primary reflector needs an active surface system in order to meet the specified surface accuracy. Each of the 180 primary surface segments forming the reflecting surface will be supported by four linear actuators, one for each corner. In the current state of the telescope, the interim active surface system provides control for the 84 segments long enough to allow completion of the rest of the reflecting surface and installation of the final actuators. The active surface is a parabola formed by 180 panels arranged in 5 rings. During the 2014 SPIE we presented the interim active surface system of 336 actuators, to operate the 3 inner rings. In order to complete the whole surface with the complete 5 rings, the project engineering team needs to install another 336 actuators for the 2 outer rings of segments. However the antenna back structure is such that the room for those actuators is reduced underneath the outer rings and in consequence the current actuators will not fit.

In this document, we present the development of a new set of alternative actuators for the LMT antenna´s outer rings, their new mechanical design which are developed to obtain a more compact geometry capable of fitting in the reduced space underneath the antenna's outer rings, we also present the advantages obtained, the design issues. Details are provided about how these actuators have been improved from the perspective of repeatability, accuracy, cost, producing time and expectancy of having final actuators for the complete surface, .Additional comments and recommendations are made for applying the lessons learned to the final actuator system.

The current actuators, improved mechanically two years ago, have been used during the early science program of the LMT/GTM, these actuators populate the 3 inner rings only, and consequently the rest of the collecting surface cannot be used, the project still has old actuators to be improved, but they cannot fit on the outer rings; a new modification had to be made in order to reduce the actuators size, as well as to further improve their performance.

9912-220, Session P9

The WEAVE focus translation system: from design to construction

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WEAVE is a new wide-field spectroscopy facility proposed for the prime focus of the 4.2m William Herschel Telescope (WHT), placed in La Palma, Canary Islands, Spain.

To allow for the compensation of the effects of temperature-induced and gravity-induced image degradation, the WEAVE prime focus assembly will be translated along the telescope optical axis. The assembly comprises the prime focus corrector with integrated ADC, a central mount for the corrector, an instrument rotator and a twin-focal-plane fibre positioner. Translation is accomplished through the use of a set of purpose-built actuators; collectively referred to as the Focus Translation System (FTS), formed by four independently-controlled Focus Translation Units (FTUs), eight vanes connecting the FTUs to a central can, and a central can hosting WEAVE. Each FTU is capable of providing a maximum stroke of ±4mm with sufficient, combined force to move the five-tonne assembly with a positional uncertainty of ±20µm at a resolution of 5µm. The coordinated movement of the four FTUs allows ±3mm WEAVE focus adjustment in the optical axis and ±0.015º tilt correction in one axis. The control of the FTS is accomplished through a PLC-based subsystem that receives positional demands from the higher-level Instrument Control System.

SENER is responsible for designing, manufacturing and testing the FTS and the equipment required to manipulate and store the FTS together with the instrument.

This manuscript describes the final design of the FTS along with the analyses and simulations that were performed, discusses the manufacturing procedures and the results of early verification prior to integration with the telescope. The plans for mounting the whole system on the telescope are also discussed.

9912-222, Session P9

Space active optics for wide-field high-angular resolution observatories

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To meet the challenges of Earth observation and astronomy, future space observatories will require telescopes of several meters in diameter. The various space environment constraints will induce deformations and misalignments of the telescope mirrors, thus degrading the optical quality of observations. The integration of active optics, used since the late 80s for alignment and preservation of the optical quality of the ground telescopes, becomes mandatory. Such a system consists of three elements: a measuring device, a correction set-up and a control loop which links both previous elements.

We present the development of a perturbations estimator minimizing the residual wave front in the telescope field of view. The analysis of this estimator and more generally of the ultimate performance of a space active optics system enabled us to highlight the impact of high spatial frequencies on optical quality. On the other hand, the presence of such high frequencies due to the primary mirror supports print through, urged us to evaluate the possibilities of their reduction in the case of large mirrors. Using a finite element model of such a mirror, we made local modifications of the mirror structure to adapt its deformation to the correcting capabilities of active optics.

We also present future trends for wide field active telescopes and the opportunity to optimize the optical combinations over subfields for dedicated instruments.

9912-223, Session P9

Active optics system for the 4m telescope of the Eastern Anatolia Observatory (DAG)

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AMOS has recently been awarded for the design, manufacturing and installation of a new 4m-class telescope for the Turkish Eastern Anatolia Observatory (DAG). The telescope is based on a Ritchey-Chretien configuration with two folded Nasmyth focal planes. The optical train is composed of three mirrors: the primary mirror (M1) with an optical aperture of 4m, a convex secondary mirror (M2), and a flat folding mirror (M3). Because the telescope will be ultimately used with an adaptive optics system in order to reach diffraction-limited performances, specific design provisions need to be implemented at telescope level for enhancement of its intrinsic quality. In particular, an active optics system needs to be developed so as to meet the challenging top-level requirements. The active optics system consists in (a) an adjustable support for M1 with a low temporal bandwidth, and (b) two hexapods supporting M2 and M3. Both M1 support and the hexapods are actively controlled during regular telescope operations.

The design of the support of the primary mirror is driven by the need of (1) minimizing the support-induced mirror distortions under telescope operating conditions, (2) shaping the mirror surface to the desired profile, and (3) providing a high stiffness against the wind loads. In order to fulfill these requirements, AMOS proposes an innovative design that consists of 66 pneumatic actuators associated to 9 hydraulic actuators that are arranged in three independent circuits. The pneumatic actuators actively compensate for low-order telescope pupil aberrations (mainly astigmatism, coma, 3rd-order spherical, trefoil and quatrefoil) that are generated by the mirror support itself or by polishing residuals on the three mirrors of the telescope. The hydraulic system is used to rigidly fix the mirror position while offering a high stiffness against wind loads. Associated with an optical feedback from a wavefront sensor, the active support of the primary mirror can be adjusted on regular basis during telescope operations so as to minimize the induced errors on the telescope pupil. Under this condition, the active support of M1 allows limiting the induced telescope wavefront aberrations to less than 20 nm RMS WFE.

In parallel, the M2 and M3 mirrors are mounted on hexapods whose position can be adjusted during telescope operations. This adjustment compensates telescope mis-alignments that regularly occur due to variations of the conditions of observations (change of temperature or tube elevation angle). The active control of the position of M2 and M3 is performed either with look-up tables (open-loop control) or using optical feedback from a wavefront sensor (closed-loop control). Hexapods with high accuracies allows positioning the M2 and M3 with a precision better than 1µm and 2 arcsec.

9912-224, Session P10

A three-layer eight-octant phase mask towards broadband high-contrast observations

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For direct detection of exoplanets, we have been developing focal-plane coronagraphic phase masks based on photonic crystals, artificial periodic nanostructures of high and low refractive indices. The photonic-crystal technology is advantageous for coronagraphic phase masks owing to its extremely small manufacturing defects. The photonic-crystal phase masks are composed of space-variant half-wave plates (HWPs), that is, HWPs with space-variant fast axes. Phase modulation required for the coronagraphic mask can be realized by utilizing the Pancharatnam-Berry's phase, which depends on orientation angles of the fast axes of the space-variant HWPs. For example, the orientation angles have to be set to +/- 45 degrees in each eight-octant sector of the mask for realizing the 0/pi phase modulation required for the 8OPM. However, the photonic-crystal HWPs exhibit chromatic characteristics because their phase retardations depend on a wavelength. In other words, extremely high-contrast observations can be realized only at an optimized wavelength. For realizing broadband high-contrast observations, polarization-filtered photonic-crystal coronagraphic masks have been proposed and developed (e.g., Murakami et al. (2010), ApJ, 714, 772; Murakami et al. (2013), Opt. Express, 21, 7400; Murakami et al. (2014), Proc. SPIE, 9143, 914334). However, the polarizing filters would cause additional wavefront aberrations, resulting in degradation of an achievable contrast. Furthermore, optical throughput of the coronagraphic system for planetary light would degrade due to the polarization filters. For resolving these problems of the photonic-crystal coronagraphic masks, we designed a three-layer 8OPM (Murakami et al. (2014), Proc. SPIE, 9143, 914334). It is expected that an extremely high contrast of 1e-10 can theoretically be realized by the three-layer 8OPM without the polarization filters over a broad wavelength range.
As an important next step, we recently manufactured a first-trial three-layer 8OPM, based on the photonic-crystal technology, optimized over a wavelength range between 500 and 800 nm. The manufactured 8OPM is composed of three-layered eight-octant HWPs with fast axes of 75.0 and 15.15 degrees (first layer), -15.0 and -74.85 degrees (second layer), and 75.0 and 15.15 degrees (third layer) in each eight-octant sector, instead of +/- 45 degrees for the previous single-layer 8OPM mentioned below. We have been carrying out laboratory experiments of the manufactured three-layer 8OPM using visible light sources to evaluate the coronagraphic performance and manufacturing errors. Here we report our recent progress on the three-layer photonic-crystal 8OPM, as well as related observational techniques, towards broadband high-contrast imaging of exoplanets.

9912-225, Session P10

Advances in starshade technology readiness for an exoplanet characterizing science mission in the 2020's

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With the discovery of so many exoplanets, it is of keen and urgent interest to characterize these planets. Starshade, an external occulter, could fly in formation with a telescope, allowing us to peer into the atmospheres of these planets and characterize them. Recent technology development, in coordination with system design, has added much needed detail to define the technology development needs for a science mission in the 2020's. This paper addresses the current state of technology for the starshade mechanical system, the successful efforts to date, and upcoming efforts. The starshade is a complicated deployable instrument that requires hundreds of joints and members to rotate, unfurl and release with exacting precision in order to provide the requisite on-orbit shape profile needed to create the 1e-10 contrast for imaging of exoplanets. The starshade is an elegant design that incorporates flight heritage and precedence to advance the footing of the starshade technology, however much work has to be performed to demonstrate that systems function together as required to meet the optical needs. The starshade mechanical instrument comprises an inner and opaque disk as well as 28 opaque petals along its periphery that limit diffraction of the starlight into the telescope.

Successful efforts have shown the ability to manufacture petals to flight tolerances, as well the ability to deploy that petals to the correct position, a key milestones for a starshade mission. Current efforts are larger in scope and require the combination of multiple systems and their system interaction. Work is being performed to define and build a half scale functioning optical shield prototype for the inner disk, a critically important member in occulting the light of the star, and a complicated subsystem in itself. Separately, having shown the ability to produce the shape of the petal to the specified tolerances, it is critically important to demonstrate the design, manufacture and test of a flight like petal with all the necessary interfaces to the rest of the system, including launch restraints and the petal optical shield. Critically important in all of the individual subsystem efforts, is definition of the full system architecture to inform and direct the subsystem design. Recent NASA funded efforts have allowed for full system mechanical definition that dovetails with potential science missions for the 2020's with telescopes such as WFIRST.

9912-226, Session P10

Development of speckle nulling technique for the Savart-plate lateral-shearing interferometric nuller for exoplanets (SPLINE)

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The Savart-plate lateral-shearing interferometric nuller for exoplanets (SPLINE) is a kind of a visible nulling coronagraph for directly imaging exoplanets (Murakami & Baba (2010), Opt. Lett., 35, 3003). One of advantages of the SPLINE is its simple configuration because it consists of only a Savart plate placed between two crossed polarizers. The Savart plate splits incoming unpolarized light beam into two orthogonally polarized ones with lateral shear. For on-axis starlight, an optical-path difference (OPD) is not introduced between the two light beams split by the Savart plate. The on-axis starlight is canceled out by the SPLINE, since a fully achromatic ϖ phase difference between the two light beams is caused by the Savart-plate placed between two crossed polarizers. For off-axis exoplanetary light, on the other hand, the Savart plate introduces an additional OPD between the two light beams which depends on an off-axis angle of the planet. Thus, the planetary light is not canceled out and can directly be detected. Theoretically the SPLINE can null the stellar light even when an entrance pupil function is complex such as segmented-mirror extremely large telescopes. However, achievable contrast of the SPLINE is limited by phase and amplitude aberrations due to imperfect optical surfaces of the optical elements. The stellar speckles caused by the aberrations disturb direct detection of exoplanets. Thus, reduction of the stellar speckles is required to improve the achievable contrast. We propose to introduce a speckle nulling technique to the SPLINE. The speckle nulling with the SPLINE is conducted in two steps; speckle field measurement on a focal plane and wavefront correction using a liquid-crystal spatial light modulator (LCSLM) on a pupil plane. For measuring the speckle field on the focal plane of the SPLINE, we propose to apply the self-coherent camera (SCC) (e.g., Galicher et al. (2008), A&A, 488, L9). A polarizing beam splitter (PBS) is replaced with the second polarizer to apply the SCC for the SPLINE. The PBS allows us to obtain bright and nulled outputs simultaneously. The nulled output (science channel) consists of both stellar light and planetary light. On the other hand, the stellar light is dominant in the bright output. By producing a reference plane wavefront from the bright output (reference channel), interference fringes between the reference and science channels are acquired on the focal plane. The speckle field can be derived by post processing based on the SCC technique. For correcting the wavefront aberrations, the LCSLM is placed behind the Savart plate of the SPLINE to introduce space-variant phase difference between two orthogonally-polarized wavefronts generated by the Savart plate. By applying appropriate phase modulation, the stellar speckles can be canceled out to create a dark hole in a certain region on the focal plane. Thus we expect that the achievable contrast of the SPLINE can be greatly improved. We report recent progress on computer simulation and laboratory experiments of the speckle nulling technique applied to the SPLINE.

9912-227, Session P10

Development and characterization of Four-Quadrant Phase Masks coronograph (FQPM)

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The goal of a coronograph is to reduce the flux of a bright object (e.g. a star) in order to distinguish its faint near environment (e.g. an exoplanet). In this context, we developed and studied the four-quadrant phase mask coronograph (called FQPM). Like all phase mask coronagraph, the FQPM uses a Lyot stop in a pupil plane to stop the stellar light that is diffracted by the focal phase mask. The planet image however is not affected by the coronagraph and is detected in the final image.

In collaboration with the GEPI laboratory, we built several monochromatic FQPM since 2000. Over the year, we have established systematic procedures for fabrication and characterization of the coronagraph. A visual inspection with a microscope is performed for every component and a dedicated test bench was set up in a clean room.

This process gives us a quick feedback on the quality and performance of the component. It enabled us to understand the influence of various parameters, such as transition, alignment of the transitions or step depth. The mask design and the fabrication process were modified and we are now able to build a FQPM for any given optimal wavelength in visible or near-infrared with a success rate close to 100%. Moreover, we improved the performance of the components, reaching attenuations of more than 10,000 on the central peak.

The best of these components are now used on the THD bench, an optical bench developed for the study of high contrast imaging techniques.

On my poster, I will present the procedure we developed to build and test the phase mask, as well as details on the performance of the FQPM coronograph.

9912-228, Session P10

Analysis of nulling phase functions suitable to image plane coronagraphy

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Coronagraphy is a very efficient technique for identifying and characterizing extra-solar planets orbiting in the habitable zone of their parent star, especially in a space environment. An important family of coronagraphs is actually based on phase plates located at an intermediate image plane of the optical system, and spreading the starlight outside the "Lyot" exit pupil plane of the instrument. In this commutation we present a set of candidate phase functions generating a central null at the Lyot plane, and study how it propagates to the image plane of the coronagraph. These functions include linear azimuthal phase ramps (the well-known optical

vortex), azimuthally cosine-modulated phase profiles, and circular phase gratings. Nnumerical simulations of the expected null depth, inner working angle, sensitivity to pointing errors, effect of central obscuration located at the pupil or image planes, and effective throughput including image mask and Lyot stop transmissions are presented and discussed. The preliminary conclusion is that azimuthal cosine functions appear as an interesting alternative to the classical optical vortex of integer topological charge.

9912-230, Session P10

Development of PIAACMC for large aperture ground-based telescopes

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The Phase Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC) is an architecture for directly observing extrasolar planets, and can achieve performance near the theoretical limits for any direct-detection instrument. The PIAACMC architecture includes aspheric PIAA optics, and a complex phase-shifting focal plane mask that provides a pi phase shift to a portion of the on-axis starlight. The phase-shifted starlight is forced to interfere destructively with the un-shifted starlight, causing the starlight to be eliminated, and allowing a region for high-contrast imaging near the star.

The PIAACMC architecture can be designed for segmented and obscured apertures, so it is particularly well suited for ground-based observing with the next generation of large telescopes. There will be unique scientific opportunities for directly observing Earth-size planets around nearby low-mass stars. We will discuss design strategies for adapting PIAACMC for the next generation of large ground-based telescopes, and present progress on the development of the focal plane mask technology. We also present simulations of wavefront control with PIAACMC, and suggest directions to apply the coronagraph architecture to future telescopes.

9912-262, Session P10

WFIRST/AFTA coronagraph contrast performance sensitivity studies: simulation versus experiment

Erkin Sidick, Byoung-Joon Seo, David S. Marx, Ilya Y. Poberezhskiy, Bijan Nemati, Jet Propulsion Lab. (United States)

The WFIRST/AFTA 2.4 m space telescope currently under study includes a stellar coronagraph for the imaging and the spectral characterization of extrasolar planets. The coronagraph employs sequential deformable mirrors to compensate for phase and amplitude errors. Using the Modelable Coronagraph Testbed (MCB) at the Jet Propulsion Laboratory, we have investigated through simulations the sensitivity of dark hole contrast in a Hybrid Lyot Coronagraph (HLC) for several error cases, including lateral and longitudinal translation of an occulting mask, lateral translation of a Lyot stop, tip/tilt of the occulting mask and the Lyot stop, DM1 and DM2 misalignment, and the occulter/Lyot masks fabrication errors. In some cases we confirmed the theoretical predictions with the testbed measured results.

9912-272, Session P10

Design and construction of a 76m long-travel laser enclosure for a space occulter testbed

Michael Galvin, Yunjong Kim, N. Jeremy Kasdin, Princeton Univ. (United States); Dan Sirbu, NASA Ames Research Ctr. (United States); Robert J. Vanderbei, Dan Echeverri, Princeton Univ. (United States); Kunjithapatham Balasubramanian, Stuart B. Shaklan, Douglas Lisman, Jet Propulsion Lab. (United States)

Princeton's High-Contrast Imaging Lab (HCIL) is expanding our space occulter testbed from 11m to 76m in order to achieve a Fresnel number that is flightlike for candidate space occulter reference missions. This expansion requires the construction of a 76m long-travel laser enclosure. Requirements for the enclosure include:

1) Light-tight

2) Large (~1m) diameter clear aperture along the whole beam path

3) Baffles at regular spacing

4) Characterization of low-reflectivity paint for inner walls

5) Characterization and mitigation of jitter and diurnal beam drift environments

6) Three accessible, enclosed optical table stations (at the midpoint and both endpoints) with manual fine alignment of each optical table

7) Modular (for further length expansion in the future).

Here we present the mechanical design and construction status of the enclosure, with a focus on the efforts made to achieve expandable modularity and use nearly all commercial off-the-shelf (COTS) or semi-COTS parts.

9912-232, Session P11

Extending ground-based astronomy into the infrared

Kyler Kuehn, Simon Ellis, Australian Astronomical Observatory (Australia)

Highly variable emission in the upper atmosphere from hydroxyl molecules significantly impedes accurate photometric and spectroscopic measurements of objects beyond the atmosphere -- where all of the targets of astronomical observations reside. Orbiting observatories are one possible solution to this problem, but they are exorbitantly expensive and upgrading (or even simply maintaining) their capabilities is extremely challenging (and dangerous). And even the highest-resolution ground-based instruments are thwarted by scattered light contaminating the interline region. But if ground-based instruments can suppress this OH emission, observations beyond wavelengths of 1 micron become far more effective.

There are several different technological solutions being developed to solve this problem, including Fiber Bragg Gratings (FBGs), demonstrated on the GNOSIS instrument and being developed further for the AAO's PRAXIS instrument. An alternative technology for suppressing specific wavelengths of light corresponding to the OH emission, and one that potentially rivals FBGs in terms of efficiency, cost-effectiveness, ease of manufacture and adaptability is micro-ring resonators. In particular, micro-ring resonators are lithographically printed in silicon, and so are very modular and possibly to integrate with other on-chip photonic components, such as array waveguide gratings.

There are several steps required to realize a functional instrument incorporating this novel technology:

1) Fabricating silicon wafers with a suite of waveguides and associated ring resonators

2) Coupling light from fibers into and out of the waveguides

3) Simulating various configurations to optimize both the desired throughput and the position and depth of OH suppression features, in parallel with engineering efforts to construct these modeled systems

4) Measurement of both throughput and suppression in a packaged system, ultimately to be incorporated into an astronomical instrument used at an observational facility.

We describe our recent progress on all four of these steps in the process of ring-resonator based OH suppression for ground-based infrared spectroscopy.

9912-233, Session P11

Laser induced satellite relay switching for data transmission in between Mars and Earth for space craft GPS navigation and telescopic data transfer for surveying and imaging using radio frequency modulation with laser beam converting transducer

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Laser beam transmitter: Laser transmitter:

To produce Laser signal for a great distance such as moon or orbiting satellite chemical laser is used where laser beam is produce by chemical reaction of halogen and hydrogen.

Laser beam produce by this mechanism is very energetic and intense. By taking laser beam from chemical laser source then passing through a fiber optic cable made up of metal – synthetic glass then by wave front division automatically making multiple beam concave, convex or plane wave.

This signal will transmit via telescopic laser transmitter as it is. In bed weather situation by combining other wavelengths of laser producing by different reaction making a mixture of wave length will be transmitted taking into account of absorption scattering reflection.

Laser beam receiver: Laser receiver (on boarded to air plane):

The receiver will be a light electric signal transducer that that will convert radio signal and other signal to laser beam

9912-234, Session P11

CHOUGH: petite ADC for a high-order adaptive optics system

Daniel Hölck, Nazim A. Bharmal, Durham Univ. (United Kingdom); Martin Black, David M. Henry, UK Astronomy Technology Ctr. (United Kingdom); Richard M. Myers, Durham Univ. (United Kingdom)

We discuss the design, construction and lab test results of a 50mm diameter Atmospheric Dispersion Corrector (ADC) for The CANARY-Hosted Upgrade for High-Order Adaptive Optics (CHOUGH). Usually to avoid pupil actuator-lenslet array mismatch, the ADC is Customarily placed very close to the pupil plane. This design aims to achieve a non-pupil conjugated ADC suitable to be located in any place inside the collimated beam path, this is due to the restrictions given by CHOUGH optical relay. The ADC also needs to satisfy the very small pupil shift requirement, for pupil stability. The ADC is of the Amici prism type, made up of two plates of cemented double prisms. The two plates counter rotate correcting for the different Zenith angles, from the Zenith up to 60°. We report on the testing methodology and the obtained labs results in order to confirm the expected correction and requirements.

9912-235, Session P11

CMB polarization modulation for the Atacama Cosmology Telescope using continuously rotating half-wave plates

Jonathan T. Ward, Univ. of Pennsylvania (United States)

The Atacama Cosmology Telescope is a six-meter diameter telescope located at 17,000 feet (5,200 meters) on Cerro Toco in the Andes Mountains of northern Chile. The ACTPol instrument is a polarization sensitive receiver featuring TES bolometer detector arrays that operate at 90 and 150 GHz. ACTPol is currently making high resolution measurements of the polarized Cosmic Microwave Background (CMB). Development of instrumentation for the next generation Advanced ACTPol (AdvACT) experiment began in late 2014 and will include the deployment of four multichroic detector arrays over the next several years. AdvACT will cover five frequency bands (28, 41, 90, 150, and 230 GHz), which will allow for cleaning of both synchrotron and dust foregrounds. At scales of $l < 100$, the primary goal of AdvACT is to measure the B-mode polarization from primordial gravitational waves generated during inflation. A key instrumental upgrade to achieve this goal is a set of three warm, continuously rotating half-wave plates (HWPs). The wave plates modulate the incoming polarization signal to drastically reduce 1/f noise and reduce polarization systematics. A fully operational rotation system based on air bearings was deployed on the ACT telescope in January 2015, followed by several iterations of prototype HWP optics. The positions of the rotating HWPs are obtained using a custom-built encoder system and software algorithm. The full design of the rotation, control, and readout system along with analysis of the mechanical performance are discussed in detail. We also present preliminary results from data taken with the rotation system operating at 2Hz, including HWP structure subtraction and demodulation technique. The final, demodulated data exhibits a significant reduction in atmospheric fluctuations allowing for the successful recovery of cosmological information at large angular scales.

9912-236, Session P11

Progress in developing a prototype simple vph-based high-resolution imaging spectro-polarimeter

Samuel C. Barden, Leibniz-Institut für Astrophysik Potsdam (Germany); Alessio Zanutta, Andrea Bianco, INAF - Osservatorio Astronomico di Brera (Italy)

We present progress on the development of a simple, imaging spectro-polarimeter that exploits the polarization dependence of volume-phase holographic gratings. When the incidence plus diffraction angles equal 90 degrees, the linear polarization state that is parallel to the fringes is diffracted and dispersed at effectively 100 percent efficiency while the orthogonal polarization state is transmitted into zeroth order without dispersion with similar efficiency. This allows the production of a high dispersion, relatively narrow band spectro-polarimeter as previously described by Barden (2012SPIE.8446E..39B). Recently, two 35 mm diameter gratings were produced at the INAF - Osservatorio Astronomico di Brera with optimal diffraction at the Hydrogen alpha line. Such volume phase holographic gratings are based on high performance Bayfol® photopolymers that made possible to perform the writing step directly on the prisms without any other glass subtrate. With this approach, it has been possible to minimize the number of optical interfaces with a potential important reduction of reflection losses and ghosts. The grating performance has been measured and a prototype instrument is

in development. Our paper will discuss the performance of the gratings and initial performance of the prototype instrument along with suggested applications for such an instrument.

9912-237, Session P11

Daytime sky polarization calibration campaign with the HiVIS spectro-polarimeter and system polarization modeling

David M. Harrington, National Solar Observatory (United States)

Calibrating the Mueller matrices of large aperture telescopes and associated coude instrumentation requires astronomical sources and several modeling assumptions to predict the behavior of the system polarization with field of view, altitude, azimuth and wavelength. Recent daytime sky based polarization calibrations of the AEOS telescope and HiVIS spectropolarimeter have provided system Mueller matrices over full telescope articulation for a 15-reflection coude system. Polarization modeling predictions using Zemax have successfully matched the altitude-azimuth-wavelength dependence on HiVIS with the few percent amplitude limitations of several instrument artifacts. Polarization predictions for coude beam paths depend greatly on modeling the angle-of-incidence dependences in powered optics and the mirror coating formulations. A 6 month HiVIS daytime sky calibration plan has been analyzed for accuracy under a wide range of sky conditions and data analysis algorithms. Comparisons between the calibration measurements, laboratory data and the Zemax model predictions with a range of coating formulations show agreement accurate enough to predict system level performance. The variation of daytime-sky derived telescope Mueller matrices with data processing algorithms and observing condition limitations along with new systems modeling tools have impact for future polarimeter design and calibration efforts on both night time and day time large aperture telescopes.

9912-238, Session P11

Progress in modeling polarization optical components for the Daniel K. Inouye Solar Telescope

Stacey R. Sueoka, David M. Harrington, National Solar Observatory (United States)

The Daniel K Inouye Solar Telescope (DKIST) will have a suite of first-light polarimetric instrumentation requiring calibration of a complex off-axis optical path. The DKIST polarization calibration process requires modeling and fitting for several optical, thermal and mechanical effects. Three dimensional polarization ray trace codes (PolarisM) allow modeling of polarization errors inherent in assuming a linear retardation as a function of angle of incidence for our calibration retarders at Gregorian and Coudé foci. Stress induced retardation effects from substrate and coating absorption, mechanical mounting stresses, and inherent polishing uniformity tolerances introduce polarization effects at significant levels. These effects require careful characterization and modeling for mitigation during design, construction, calibration and science observations. Modeling efforts, amplitude estimates and mitigation efforts will be presented for the suite of DKIST calibration optics planned for first-light operations.

9912-239, Session P11

System polarization modeling and calibration strategies for the Daniel K Inouye Solar Telescope (DKIST)

David M. Harrington, National Solar Observatory (United States)

The Daniel K Inouye Solar Telescope (DKIST) polarimetric instrumentation requires very high accuracy calibration of a complex coude path with an off-axis f/2 primary mirror, time dependent optical configurations and substantial field of view to accomplish the critical science observations. Accurate polarization predictions across a diversity of optical configurations, tracking scenarios, slit geometries and vendor coating formulations are critical to the telescope and instrument development efforts for both the design and fabrication process as well as during calibrations and post-processing mitigation efforts. Recent successes in daytime sky polarization calibrations and Zemax system polarization modeling of the 4m AEOS telescope and HiVIS spectropolarimeter show feasibility of making reasonably accurate system performance predictions. AEOS and HiVIS are a DKIST analog with a many-fold coude optical feed creating 100% polarization cross-talk with altitude, azimuth and wavelength. Predictions of polarimetric performance for the DKIST first-light instrumentation suite have been created under a range of configurations. These new modeling tools and predictions have substantial impact for the design and calibration process in the presence of manufacturing issues, science use-case based performance predictions and ultimate system limitations in the complex DKIST optical train.

9912-263, Session P11

An efficient stable optical polariser module for calibration of the S4UVN earth observation satellite

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We describe here an optical polariser module intended to deliver well characterised polarised light to an imaging spectrometer instrument. The instrument in question is the Sentinel-4/UVN Earth observation spectrometer due to be deployed in 2019 in a geostationary orbit. The polariser module described here will be used in the ground based calibration campaign for this instrument. One critical task of the calibration campaign will be the highly accurate characterisation of the polarisation sensitivity of instrument. The polariser module provides a constant, uniform source of linearly polarised light whose direction can be adjusted without changing the output level or uniformity of the illumination.

Essentially, the polariser is a collimator that provides a collimated beam of about 80 mm diameter from a small, localised and central field. The size of this field is a few arcminutes. The collimated light is to be provided within the two instrument passbands in the UV-VIS (305 – 500 nm) and the NIR (750 – 775 nm). The design presented here is a transmissive design with collimation provided by an achromatic doublet consisting of a calcium fluoride and silica lens pair. Of course, choice of lens materials is dictated by the requirement for transmission into the UV; selection of optical glasses is no longer an option. Close to the focal plane, where the small object target is located, a small crystal module linearly polarises the light. Illumination of the object target is either via a continuum light source or a tunable laser source depending on the specific calibration activity.

The polarising crystal arrangement is loosely based upon a Glan-Taylor polarising prism. The Glan-Taylor polariser transmits the extra-ordinary polarised ray whilst rejecting the ordinary ray by total internal reflection. However, the transmitted extra-ordinary ray is close to the critical angle and it experiences some loss which is significantly dependent upon the ray angle. A critical requirement, however, of the polariser module is that

the illumination is uniform across the exit pupil. In addition, the classical Glan-Taylor arrangement also introduces image ghosts from reflection of the front and rear facets. Therefore, a novel, modified arrangement is proposed. To avoid ghost reflections from front and rear facets of the prism, the prism is specially cut such that both facets are presented at the Brewster angle to the extra-ordinary ray. Ghost reflections are reduced to insignificant levels. Pupil uniformity is enhanced by combining two sets of prisms in opposing orientations.

A detailed tolerancing analysis of the design is presented, paying particular attention to the orientation of the polarising prisms and their manufacturing tolerances. Further analysis of polarisation sensitivity effects, such as stress induced birefringence will be presented together with accompanying thermo-mechanical analysis. Since the straylight performance of the instrument itself is to be characterised in great detail, it is necessary to model the straylight performance of the polarisation module and results of this analysis are presented here.

9912-240, Session P12

IMU based attitude sensor: analysis and modeling of noises and performance improvement by sensor fusion and filtering

Nirmal K., Sreejith Aickara Gopinathan, Joice Mathew, Mayuresh N. Sarpotdar, Ajin Prakash, Margarita Safonova, Jayant Murthy, Indian Institute of Astrophysics (India)

We describe the modeling and measurement of the noise in an IMU based attitude sensor. This attitude sensor is used in a balloon borne pointing system which is intended to carry out observations in ultraviolet regime. Different analysis, such as Allan Variance and Power Spectral Density (PSD) analysis are done on the IMU to identify and estimate the measurement noises.

We modeled the IMU measurement noise as a Gaussian probability density function and formulated a Kalman filter to combine accelerometer and gyroscope reading to obtain more accurate attitude estimation rather than attitude estimated from accelerometer or gyroscope.

The design and development of different digital smoothing filter such as moving average, Savitzky Golay implemented to filter the noises in IMU, their performance and drawbacks are also explained.

9912-241, Session P12

Photoconductive deformable mirrors as potential technology for astronomical instrumentation

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Photo controlled deformable mirrors (PCDMs) are based on an electrostatic membrane mirror where a photoconductive material replaces the conventional electrode pads, so that the mirror surface deforms according to a light pattern projected on the photoconductor. As a consequence, the number, shape and size of the actuators can be optimized according to the corrections to the wavefront to be performed.

In order to open the route towards applications of PCDMs in astronomical field, the increase of the mirror aperture and the improvement of the performances (response speed, maximum displacement) are required. This can be achieved by a suitable design and selection of the photoconductive material.

Here, we report the modelling of PCDMs, defining the key parameters both geometrical and physical that affect the mirror performances.

We applied this approach to both inorganic and organic photoconductors, highlighting the advantages and drawbacks of both technologies. In this way general guidelines to the best choice of the photoconductive layer are provided, focusing mainly to the potential application in astronomical instrumentation.

9912-242, Session P12

Low cost single-mode fiber Etalon for sub-m/s wavelength calibration

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A fundamental limitation of precision radial velocity measurements is the accuracy and stability of the calibration source. Here we present a low cost alternative to classical systems that utilises a single-mode fibre Fabry-Perot etalon. There are three key elements: i) a fibre etalon with a TEC; ii) a Rb saturation absorption spectroscopy setup; iii) a tunable laser and data acquisition system. We simultaneously measure the Rb transitions near 780.2nm and the closest etalon line. A PID loop controls the etalon temperate to maintain the position of its combs with an RMS error <10cm/s in a 10 minute integration.

The fibre etalon is manufactured by Micron Optics, Inc. to have a finesse of ~40 and a ~400um cavity (giving a FSR of 0.3nm @ 780nm). The etalon used is designed to maintains this finesse for the entire visible band, but other options for use in the NIR and IR regime are also available. The etalon is enclosed with a small thermoelectric cooler. This allows the transmission spectrum to be turned using small changes in temperature. The small size of the cavity allows for relatively quick changes (multiple degree changes can settle in less than a second). A saturation absorption spectroscopy setup allows for precise measurements of the Rb D2 hyperfine transition lines. These lines are known to be very stable (frequency stable to better then 1 in 10^12) and thus provide an excellent reference for calibrating the fibre etalon.

A combined optical path allows the same tunable laser source to simultaneously measure both the Rb hyperfine absorption lines and the etalon combs spectrum. Each spectrum is measure by using a photodiode and a synchronised high-speed analogue-to-digital converter. The Rb spectrum is used as an absolute reference to fix, and ultimately lock, the wavelength of the etalon peaks by varying (or maintaining) the temperature of its cavity. This information feeds a PID control loop that changes the set point of a small TEC controller at a rate of 2-3Hz. The TEC controller itself is a custom board based on the Analog Technologies, Inc. TECA1 chip. Combined with the Rb locking signal it achieves temperature stability of a few mK, which translates to 10s of cm/s error shift in the etalon combs wavelengths.

The etalon spectrum is transmitted to a spectrograph using a series of single-mode fibre switches to swap the input and output of the etalon to between a white light source and the tunable laser to feed either the spectrograph or Rb locking setup respectively. This option will provide a time-domain multiplexing of the etalon between feeding the spectrograph and feeding the locking setup. This also allows for a degree of exposure control by limiting the amount of calibrating light reaching the spectrograph.

9912-243, Session P12

An astro-comb calibrated solar telescope to search for the radial velocity signature of Venus

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Detecting terrestrial exoplanets in the habitable zones of Sun-like stars using the radial velocity (RV) method is currently challenged by perturbations induced by stellar surface inhomogeneities including spots, plages and granules leading to jitter in the measured stellar RV. Such stellar jitter is not well understood and is difficult to study in stars other than the Sun because their surfaces are unresolved. We are therefore observing the RV of the Sun by using a small, low-cost solar telescope and the HARPS-N spectrograph, calibrated with a green astro-comb, a laser frequency comb optimized for calibrating high-resolution astrophysical spectrographs. This simple solar telescope, consisting of a lens feeding an integrating sphere and coupled to the HARPS-N spectrograph via an optical fiber, now operates automatically, every clear day. We characterized this telescope both in the lab and on-sky to insure: (i) sufficient scrambling by the integrating sphere; (ii) insensitivity to guiding; and (iii) consistent throughput, independent of acceptance angle such that light from the Sun fed to HARPS-N mimics the light of an unresolved star. We recently demonstrated sub-m/s sensitivity in measuring the Earth-Sun RV with this instrument. Daily observations of the Sun will allow us to characterize the sources of stellar RV jitter; and with the help of solar satellites such as the Solar Dynamics Observatory (SDO), we will characterize the correlation between observed RV and detailed imaging of the solar photosphere. We plan to use these tools to mitigate the effects of stellar jitter with the goal of the detection of Venus from its solar RV signature, thus showing the potential of the RV technique to detect true Earth-twin exoplanets.

9912-244, Session P12

NASA's physics of the cosmos and cosmic origins programs manage Strategic Astrophysics Technology (SAT) development

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The strategic astrophysics missions of the coming decades will help answer the questions "How did our universe begin and evolve?" and "How did galaxies, stars, and planets come to be?" Enabling these missions requires advances in key technologies far beyond the current state of the art. NASA's Physics of the Cosmos (PCOS) and Cosmic Origins (COR) Program Offices manage technology maturation projects funded through the Strategic Astrophysics Technology (SAT) program to accomplish such advances. The PCOS and COR Program Offices, residing at the NASA Goddard Space Flight Center (GSFC), were established in 2011, and serve as the implementation arm for the Astrophysics Division at NASA Headquarters. We present an overview of the Programs' technology development activities and the current technology investment portfolio of 23 technology advancements. We discuss the process for addressing community-provided technology gaps and Technology Management Board (TMB)-vetted prioritization and investment recommendations that inform the SAT program. The process improves the transparency and relevance of our technology investments, provides the community a voice in the process, and promotes targeted external technology investments by defining needs and identifying customers. The Programs' priorities are driven by strategic direction from the Astrophysics Division, which is informed by the National Research Council's (NRC) "New Worlds, New Horizons in Astronomy and Astrophysics" (NWNH) 2010 Decadal Survey report, the Astrophysics Implementation Plan (AIP), and the Astrophysics Roadmap "Enduring Quests, Daring Visions." These priorities include technology development for missions to study dark energy, gravitational waves, X-ray and inflation probe science, and large far-IR and UV/optical/IR telescopes to conduct imaging and spectroscopy studies. The SAT program is the Astrophysics Division's main investment method to mature technologies that will be identified by study teams set up to inform the 2020 Decadal Survey process on several large astrophysics mission concepts.

9912-245, Session P12

Development of high-resolution arrayed waveguide grating spectrometer for astronomical applications: first results

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Astrophotonics is a promising new approach that provides the means to miniaturize next-generation spectrometers for large telescopes and make them more robust and inexpensive. Our research group is developing an on-chip photonic spectrograph to be used for astronomical applications in the near infrared bands (J Band: 1.1-1.4 microns; H band: 1.4-1.7 microns). The target requirements for our spectrograph are: moderate resolving power (~3000), wide spectral range (J and H bands), free spectral range of about 20nm, low on-chip loss of about 20% (1 dB loss), low crosstalk between adjacent on-chip wavelength channels of about 0.1% (-30 dB) and uniform spectral response. A promising photonic technology to achieve these requirements is Arrayed Waveguide Gratings (AWGs).

We have developed our preliminary AWG device using a silica-on-silicon substrate with a very thin layer of Si_3N_4 in the core of our waveguides. We use electron beam lithography to write the AWG pattern to ensure precision and that no gaps are introduced at the interfaces of different geometries on the chip. The waveguide bending losses are minimized by optimizing the geometry of the waveguides. We use 2.8-micron wide and 0.1-micron high silicon nitride core buried inside 15-micron thick SiO_2 cladding. Our first device designed for H band has a resolving power of ~1350 and free spectral range of ~9.5 nm around a central wavelength of 1600 nm. The device footprint is only 12 mm ? 6 mm. The device is broadband (1500-1650 nm), has minimum on-chip loss of about 35% (1.8 dB loss) and crosstalk of about 1% (-20 dB). These results confirm the

functionality of our design, fabrication and simulation methods. Currently, the device is designed for TE polarization and all the results are for TE mode. We are developing separate J- and H-band AWGs with higher resolving power and throughput and lower crosstalk over a wider free spectral range to make them better suited for astronomical applications.

9912-246, Session P12

A monolithic Michelson interferometer-based very high precision Doppler calibration source

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Searching for habitable Earth-like planets around other stars is one of NASA's major objectives for its space missions. This requires ground-based Doppler spectrographs to reach ~0.1 m/s radial velocity (RV) calibration precision or better to detect (Doppler surveys) or characterize (space transit survey follow-ups) of low-mass planets. However, current RV calibration precision with traditional Thorium-Argon (ThAr) emission lamps can only reach about 0.3 m/s. The technical issues, such as the sparse line density, flux variation, and lamp aging, have limited ThAr emission lamps to this calibration precision. Alternative calibration sources need to be developed to meet the next generation Doppler measurement requirements.

At UF, substantial progress has been made in developing a new calibration source based on a UF patented Monolithic Michelson Interferometer for the TOU optical very high resolution spectrograph (R=100K, 0.38-0.9 microns, 0.7 m/s long-term RV stability) and FIRST near infrared high resolution spectrograph (R=50K, 0.9-1.8 microns). It consists of a temperature-controlled monolithic Michelson interferometer fed with a continuum light source through a multiple mode fiber. It creates sinusoidal spectral lines over a very broad band (0.38-1.8 microns). The light beam interference between the two interferometer arms produces dense sinusoidal combs. This new Sine calibration source has demonstrated ~0.3 m/s RMS scatters over ~12 days with TOU measurements while the median photon limited RV uncertainty is 0.08 m/s. A major effort is being carried out to reduce the non-photon measurement errors while the planned replacement of the tungsten lamp with a broad-band super-continuum would double the photon-limited precision. The latest improvement results will be presented.

9912-248, Session P12

Auxiliary free space optical communication project to ensure continuous transfer of data for DAG the 4m telescope

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The continuity of the amount of data that the 4m DAG (Eastern Anatolia Observatory in Turkish) telescope will produce and transfer to Ataturk University is critical not to jeopardize the science programs. Though the fiber optics and radio link infrastructures are in place, these systems are still volatile against earthquakes, and possible excavation damages. Thus the 4m DAG telescope will be equipped with a free space optical communication system to ensure the continuity of the data transfer as a backup system. In order to cope with the disturbances introduced by the atmospheric turbulence, the transceiver FSO system will be equipped with a wavefront corrector. In this paper, the cassegrain optical design, and working principle of this system as well as expected performance analyses will be presented.

9912-249, Session P12

Adaptive optics fed single-mode spectrograph for high-precision Doppler measurements in the near-infrared

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We present the design and preliminary results for a high resolution near infrared spectrograph. It is fed by a single mode fibre coupled to a high performance adaptive optics system, leading to an extremely stable instrument with high total efficiency. The optical design is a cross dispersed Echelle spectrograph based on a white pupil layout. The instrument uses an R6 Echelle grating with 13.3 grooves per mm, enabling very high resolution with a small beam diameter. The optical design is diffraction limited to allow for optimal performance; this leads to subtle differences compared to spectrographs with large input slits.

9912-250, Session P12

Optical system for Galaxy Evolution Spectroscopic Explorer (GESE)

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The scientific goal of GESE mission is to answer the question: How did galaxies evolve into the spiral, elliptical, and irregular galaxies that we see today? This paper concerns the optical tools needed to achieve this goal. A UV multi-object slit spectrometer is designed to conduct a large ultraviolet spectroscopic survey of galaxies at a redshift, z~1-2. A camera is designed to acquire the target galaxies in the slits of the spectrometer. A Digital Micromirror Device (DMD) serves as a slit mask, sending light from the target galaxies to the spectrometer, and light from the remainder of the field of view, to the camera. This paper focuses on the designs of the 1.2m Three-Mirror Anastigmat (TMA) telescope and the "offner like" spectrometer and camera. In the latter design, the spherical mirrors in the offners, for both spectrometer and camera, are replaced with free-form aspheric mirrors in order to achieve the required spectral and special resolutions over the large field of view. The optical alignment and metrology will also be addressed. Finally, the connection between the science goal and optical system specification is also presented.

9912-251, Session P12

Optimizing small space telescopes

Tony B. Hull, The Univ. of New Mexico (United States); Sara R. Heap, NASA Goddard Space Flight Ctr. (United States)

Science-driven metrics are convolved with current technology to seek an optimum approach to small space telescopes. Our optimization is for cost, since cost includes management of risk, robustness of optical design, resilience to thermal environments, and overall opto-mechanical stability. These factors will be discussed in the context of the 1.2m Galaxy Evolution Spectroscopic Explorer (GESE) mission concept.

9912-264, Session P12

Back-propagating the light of field stars to probe Euclid mirrors aberrations

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To meet Euclid's stringent requirements on the PSF knowledge, we propose a wavefront based method to estimate the PSF over the whole field of view. Indeed, the PSFs at every position of the field of view are fully characterized by aberrations of each optical surface of the telescope and can be computed using Fourier beam propagation (Roey et al. 1981, J. Opt. Soc. Am., 71, 803). Although these aberrations can be calibrated on ground, it is probable that they will not remain stable enough after launch. One possible way to measure the wavefront on orbit would be to strongly defocus and refocus the telescope, an operation that is highly risky and that will not be implemented by ESA.

We therefore propose a method to use scientific observations to estimate wavefront aberrations on the few optical surfaces of Euclid telescope. It uses each observed bright star as a source of a coherent plane wave to probe these aberrations in the same manner it was already done for diffraction tomography (Kamilov et al. 2015, Optica, 2, 517). This method will monitor the surface of every Euclid's mirrors bringing a new access to all its optical component status without any need to move optical elements. In addition, as it will use stars present in the scientific channel, it will not require any additional calibration time. Finally, the knowledge of these optical surfaces will give the mean to estimate the PSF at all wavelength and in each point of the field of view solving the problem of PSF interpolation on positions of lensed galaxies.

This problem of determining mirrors aberrations using many images of stars is solved in an inverse problem framework. For each star, the forward model is free space propagation of a plane wave (whose angle is given by the star position) across the telescope optics ended by intensity recording in the detector plane. This model is non linear, however, as propagation between each mirror is a linear operation, modeling errors can be back propagated and used to update the estimated aberrations of each mirrors. These back propagated errors for many stars across the field of view are used by a continuous optimization algorithm (VMLMB, Thiébaut 2002, SPIE Proc. 4847, 174-183) to probe precisely these aberrations. In this algorithm, the phase retrieval problem given the measured intensity is solved by the mean of an adapted proximity operator (Schutz 2014, J. Opt. Soc. Am. A 31, 2334-2345). In this communication, we will present results on simulated data for a simplified Euclid telescope model for both narrow and broad band.

9912-265, Session P12

Optimization of high sensitivity parametric transducers for the Gravitational Wave Detector "Mario Schenberg".

Vincenzo Liccardo, Instituto Tecnológico de Aeronáutica (Brazil); Elvis Ferreira, Rogeiro Oliveira, Odylio Aguiar, Instituto Nacional de Pesquisas Espaciais (Brazil)

The Mario Schenberg Gravitational Wave Detector, which has a spherical resonant antenna, started commissioning operation on September 2006 and involves collaboration between many Brazilian institutions such as INPE, USP, ITA, IFSP and also some foreign universities. The Schenberg antenna is the only spherical antenna equipped with a set of parametric transducers for gravitational wave detection. When coupled to the detector, transducers are able to monitor its mechanical quadrupolar modes. On the basis of the recent good results obtained in terms of sensitivity, a new set of transducer, which makes use of superconducting reentrant cavities, are being developed at the National Institute for Space Research (INPE). In this work we will establish a systematic procedure to manufacture high sensitivity transducers with the aim of obtaining Q-factors of the order of 10^5 in cryogenic conditions.

9912-266, Session P12

The Reconnaissance & Early-warning Optical System Design for Dual Field of Space-Based "Solar Blind Ultraviolet"

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With the development of modern technology, especially the development of information technology at high speed?the ultraviolet (UV) early warning system plays an increasingly important role. In the modern warfare, how to detect the threats earlier, prevent and reduce the attack of precision-guided missile has become a new challenge of missile warning technology [2]. Because the ultraviolet warning technology has high environmental adaptability, the low false alarm rate, small volume and other advantages, in the military field applications it has been developed rapidly .

The ultraviolet optical system is in the forefront of the ultraviolet early warning system, so it is equivalent to the eye of the entire system. Its main task is to collect the infrared radiation from the target and background to the detector. For the UV early warning system, the optimal working waveband is 250 nm ~280 nm (Solar Blind UV) due to the strong absorption of ozone layer .

According to current application demands for solar blind UV detection and early warning, this paper proposes a reconnaissance & early-warning optical system, which covers solar blind UV (250nm-280nm) and dual field. This structure takes advantage of a narrow field of view and long focal length optical system to achieve the target object detection, uses wide-field and short focal length optical system to achieve early warning of the target object. It makes use of an UV beam-splitter to achieve the separation of two optical systems. According to the detector and the corresponding application needs of two visual field of the optical system, the calculation and optical system design were finished. A single pixel energy concentration is greater than 80%.

The paper is organized as follows. Section one systematically expounds the principle of ultraviolet-detection technology and detector devices of the structure and performance. The development of ultraviolet early warning system at home and abroad is introduced Designs the missile simulation systems and the ultraviolet-objective of alarm systems were summarized. Section two tries to state the working principle of the reconnaissance & early-warning optical system. Section three completes the work of the

study and the optical system design of the reconnaissance & early-warning optical system. This work includes the calculation of the parameter of the optical system, the selection of original configuration and the optimization of the solar blind ultraviolet optical system. Section four gives the design results and evaluation of image quality.

9912-84, Session 16

Advances in far-ultraviolet reflective and transmissive coatings for space applications

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Exploitation of far ultraviolet (FUV, 100-200 nm) observations extends to most areas of modern astronomy, from detailed observations of Solar System objects, the interstellar medium, exoplanets, stars and galaxies, to studies of crucial cosmological relevance. Despite several developments in recent decades, yet many observations are not possible due to technical limitations, of which one of the most important is the lack of optical coatings with high throughput. Development and optimization of such efficient FUV coatings have been identified in several roadmap reports as a key goal for future missions. The success of this development will ultimately either improve the performance of nowadays feasible optical instruments or enable new scientific imaging capabilities.

In this communication, FUV coatings for space observations developed at GOLD will be reviewed. These coatings include transmittance filters, narrowband mirrors, along with efficient polarizers.

Hence we will present the performance of narrowband and broadband transmittance filters based on Al and MgF_2. These filters are tuned on several spectral lines or bands in the FUV, presenting a high peak-to-visible rejection ratio with a good FUV performance.

New advances in reflective coatings will be also shown. Reflectors based on either combinations of MgF_2 and LaF_3 or combinations of LiF, Al, and SiC have been developed. Target ranges include lines of high interest for space observations, such as H Lyman ? (121.6 nm) and ? (102.6 nm), OI (130.4 nm), and OVI (103.2-103.8 nm).

Finally, we will also show our recent developments on coating polarizers based on Al and MgF_2, which are tuned at H Lyman ? line and operate either by reflectance or transmittance. Reflective polarizers present a high throughput; moreover, a new concept of transmissive polarizers including spectral filtering properties (such as narrowband profile and visible rejection) has been designed and preliminarily tested.

9912-85, Session 16

Use of plasma enhanced ALD to construct efficient interference filters for astronomy in the FUV

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Our program uses a range of materials to implement stable optical layers suitable for protective overcoats with high UV reflectivity and unprecedented uniformity, and use that capability to leverage innovative ultraviolet/optical filter construction to enable a range of observational astronomical science in the far ultraviolet (FUV). The materials we will use include aluminum oxide and hafnium oxide (as an intermediary step for development only) and progressing to a range of fluoride-based compounds (for production). These materials are deposited in a multilayer format over a metal base to produce a stable construct. Specifically, we will employ the use of PEALD (plasma-enhanced atomic layer deposition) methods for the deposition and construction of reflective layers that can be used to construct unprecedented filter designs for use in the ultraviolet. Our designs indicate that by using PEALD, we can further reduce adsorption and scattering in the optical films as a result of the lower concentration of impurities and increased control over the stoichiometry to produce vastly superior quality and performance over comparable traditional thermal ALD techniques currently being developed by other NASA-funded groups.

Our program seeks to demonstrate several things:

• That films of material can be deposited as a demonstration of the approach using PEALD techniques to produce low-loss oxide films of materials such as Si, Hf and Al. The resulting coatings will be of a thickness and a purity far higher than can be delivered by current techniques that involve sputtering deposition.

• That using the same deposition techniques, PEALD can be used to deposit thin (10s of nm) low-loss films of fluoride materials such as MgF_2, LiF, AlF_3, LaF_3, CaF_2, BaF_2 that will be used as protective overcoats for materials that can easily be oxidized by exposure to air.

• That Al deposition, protective layer deposition and characterization can be completed in-situ. Such a controlled environment will minimize the oxidation forming undesirable compounds, to improve the reflectivity of the resulting films and their interfaces by reducing scattering and adsorption.

• That deposition of such protective overcoats over aluminum metal can be achieved with PEALD to provide a sufficiently crystalline, uniform and stable structure that extend the range of diagnostic emission and absorption lines available for science.

• To apply multiple alternating layers of metals and dielectrics using our PEALD approach to produce multi-cavity structures exhibiting very high performance. This goal is currently limited by the inability to deposit very thin layers with great accuracy, while demonstrating film toughness and 'bulk' thin film material losses.

• To apply the PEALD approach to the construction of multi-layer dielectric layers to act as reflection filters or high reflectors in narrow band systems.

• To similarly construct multi-layer broadband reflective surfaces which are thought to exhibit higher performance than metal-based mirrors (using a short wave extension to prototype dichroics our group is already developing for space).

9912-86, Session 16

Update on UCO's advanced coating lab development of silver-based mirror coatings

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States); Christopher T. Ratliff, Michael Bolte, David J. Cowley, Univ. of California Observatories (United States)

We present progress in efforts underway at the University of California Observatories to develop high performance durable silver-based mirror coatings for telescope and instruments. Silver-based coatings are extremely prone to tarnish and/or corrosion, and successful coatings depend not only on the materials used but also the deposition processes employed. Our PVD deposition chamber allows both sputtering and ion-assisted e-beam depositions for head-to-head comparison of deposition processes, and we present results of these comparisons. We present a systematic study to determine which oxides, nitrides and fluorides provide the best protection in environmental tests. We are exploring a number of new materials that show some promise for increased durability. We also report on our further studies using Atomic Layer Deposition (ALD) over-coating of Ag, which a pilot study demonstrated significant benefit to durability. We also describe our large ALD research chamber currently under construction that will demonstrate ALD processes on larger substrates (70 cm diameter). This chamber should be operational around the time of the conference.

9912-87, Session 16

Advanced astronomical filter design: challenges, strategy, and results to meet current and future requirements

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The Observatorio Astrofísico de Javalambre in Teruel, Spain (OAJ) is a astronomical facility whose primary role will be to conduct all-sky astronomical surveys. The OAJ facility has a wide-field telescope, the JST/T250; a 2.55 m telescope with a 3º diameter field of view (FoV) designed to perform the Javalambre Physics of the Accelerating Universe Astrophysical Survey (JPAS). In addition the Javalambre Auxiliary Survey Telescope (JAST/T80) is an 80 cm Ritchey Chrétien telescope with a 2º diameter FoV, particularly defined for carrying out large sky photometric surveys. For both telescopes challenging steep edge narrow bandpass filters are needed requiring the development of new filter designs. The filters had typically a FWHM bandwidth of 14.5 nm and center wavelengths (cwl) from about 380 nm to 900 nm.

The filters work under fast convergence and observe with a mosaic of multiple filters simultaneously. Therefore the filters must have outstanding performance to ensure high quality scientific image. Due to the requirement of broad blocking and low reflectivity a combination of color glass (absorption filter) and coated clear glass (interference filter) was used. In order to assure the image quality the effective refractive index of the filter assembly had to be determined and the filter thickness was adopted by optical design simulations for each filter. Measuring the wavelength dependent refractive index of color glass is difficult since color glass absorbs light and a measurement method based on transmission is not sufficient. Here a prism coupling method was necessary for the wavelength dependent refractive index determination of the used color glass. Based on these measurements the filter assembly was designed and used for optical design of the whole system to determine the effective filter thickness used for the final filter. In addition the transmitted wavefront error (TWE) over the clear aperture of about 100 mm x 100 mm had to be strictly below lambda/2 at 633 nm. Due to the broad blocking of the narrow bandpass filter, a standard TWE measurement was not possible. Therefore a new white-light Shack Hartmann wavefront measurement system was needed that measures the TWE at the passband. Moreover the spectral edges have to be steep for a small transition width from 5% to 80% and so typically a 6 cavity interference filter design had to be chosen. The steep edges together with a center wavelength uniformity (< ±0.2 %), high transmission (Tmax > 85 %), and broad blocking (out of band blocking with average transmission less than 10-5 from 250 nm and up to 1050 nm) lead to an interference filter design of well above 100 layers and a total coating layer thickness of a few micrometers. The final filter assembly consisting of color glass and coated clear glass were fully characterized and fulfilled the spectral, the transmitted wavefront, and final scientific image quality requirements due to the chosen design, characterization of all sub-components, and manufacturing strategy.
All these requirements have to be fulfilled for an operation temperature between -20°C and + 20°C.

9912-88, Session 16

Advanced optical coatings for astronomical instrumentation

Fabien Pradal, REOSC (France)

Recently REOSC worked and progresse on various thin film technology for : Large mirrors with low stress and stabel coatings

Large lens elements with strong curvature and precise layer specifications

Large filters with high spectral response uniformity specifications

IR coatings with low stress and excellent resistance to cryogenic environment for NIR to LWIR domains.

Results will presented and discussed on the basis of several examples.

9912-89, Session 17

The broad-band vector Apodizing Phase Plate (vAPP) coronagraph: NIR liquid crystal performance and future developments

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The Apodizing Phase Plate (APP) is a phase-only pupil-plane coronagraph that suppresses starlight in a predefined region (typically D-shaped and 2 to 7 lambda/D) by several orders of magnitude. Being located in the pupil plane its performance is insensitive to residual tip-tilt variations.

Using liquid crystal technology we developed a novel and improved version of the APP: the broadband vector Apodizing Phase Plate (vAPP). The vAPP consists of an achromatic half-wave retarder pattern with a varying fast axis on <10 micron spatial scales. The fast axis encodes the required phase pattern through the vector phase, while multiple twisting liquid crystal layers produce a nearly constant half-wave retardance over a broad wavelength range. The liquid crystal manufacturing method allows a high control of the phase of the plate with high spatial resolution and a broad-band near half-wave retardance. Because the pupil phase pattern is antisymmetric, this device produces two complementary PSFs with dark holes on opposite sides, after splitting opposite circular polarizations. To enable easy installation in existing instruments a phase ramp is added to the vAPP phase pattern that splits the two PSFs without adding optics, effectively creating a coronagraphic polarization grating (aka grating-vAPP / gvAPP).

After shortly explaining the principle behind the vAPP we present a progress update of its on-sky performance in terms of the broad-band NIR (2 to 5 micron) achromaticity (zeroth order leakage / retardance) and throughput. These values are derived from on-sky measurements with the

vAPP coronagraph installed on MagAO/Clio2.

As the gvAPP is one of the baseline coronagraphs for E-ELT/METIS we furthermore present phase designs that can be implemented on the E-ELT. This includes both conventional D-shaped designs and 360 degree suppressing solutions which use the leverage provided by the high spatial resolution of liquid crystal manufacturing.

9912-90, Session 17

Mathematical modeling and experimental evaluation of a ferrofluid deformable mirror for high-contrast imaging

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Deformable mirrors (DMs) are an enabling and mission-critical technology in any coronagraphic instrument designed to directly image earth-like exoplanets in the habitable zone of their parent stars. In order to maximize the number of characterizable planets, a space-borne observatory with this mission must achieve a high degree of contrast between a target star and the region of space surrounding it, and this high-contrast search region must be as large as possible. Stellar coronagraphs designed to achieve this capability suffer from optical aberrations, which create speckles that compromise the contrast over this field of view. Closed-loop wavefront control techniques, implemented with deformable mirrors, must suppress---to the order of 10^{-10} over the search window--any speckles which might obscure or be indistinguishable from a planet. A new ferrofluid deformable mirror technology for high-contrast imaging is currently under development at Princeton, featuring a flexible optical surface manipulated by the local electromagnetic and global hydraulic actuation of a reservoir of ferrofluid. The ferrofluid DM is designed to prioritize high optical surface quality, high-precision/low-stroke actuation, and excellent low-spatial-frequency performance---capabilities which meet the unique demands of high-contrast coronagraphy in a space-based platform. To this end, the ferrofluid medium continuously supports the DM facesheet, a configuration which eliminates actuator print-through (or, quilting) by decoupling the nominal surface figure from the geometry of the actuator array. The global pressure control decouples focus control from the local actuation, bestowing the device with a mode of high-fidelity low-order control impossible with contemporary technologies. Mediated by the pressure and magnetic body force within the ferrofluid, the hydraulic actuator and electromagnetic transducer array shape the flexible facesheet by controlling the distribution of the transverse load across its surface. Here we describe this interaction with an analytical model for the two-dimensional quasi-static deformation response of the DM facesheet to both magnetic and pressure actuation. These modeling efforts serve to (a) identify the key design parameters (e.g., facesheet thickness, actuator size/strength, fluid reservoir depth, or mechanical boundary conditions) and quantify their contributions to the DM response, (b) model the relationship between actuation commands and DM surface-profile response, and (c) predict performance metrics such as achievable spatial resolution and stroke precision for specific actuator configurations. Our theoretical approach addresses the complexity of the boundary conditions associated with mechanical mounting of the facesheet, and makes use of asymptotic approximations by leveraging the three distinct length scales in the problem---namely, the low-stroke ($\sim$nm) actuation, facesheet thickness ($\sim$mm), and mirror diameter ($\sim$cm). In addition to describing the theoretical treatment, we report the results of laboratory experiments with our most recent prototype and compare our models with the experimental observations.

9912-91, Session 17

Advanced coronagraph designs for segmented aperture telescopes

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Current state-of-the-art high contrast imaging instruments take advantage of a number of elegant coronagraph designs to precisely suppress starlight and image nearby faint objects, such as exoplanets and protoplanetary disks. However, the ideal performance of coronagraphs depends strongly on the shape of the telescope aperture. Large primary mirrors tend to have segmented pupils with various obstructions, which often result in severe limitations on the ideal contrast performance of conventional coronagraph designs. We present optical systems that take advantage of numerically optimized amplitude and phase masks to provide improved performance with realistic telescope apertures. The planet to star contrast is enhanced over a relevant field of view and broad wavelength range without significant loss in throughput. We use synergistic design methods that may be applied to arbitrary apertures, including large ground-based telescopes, such as Keck and the Thirty Meter Telescope (TMT), as well as potential next-generation space telescopes.

9912-92, Session 17

Digital adaptive coronagraphy using SLMs: promising prospects of a novel approach, including high-contrast imaging of multiple stars systems

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We introduce a new technological framework for high-contrast coronagraphy, namely digital adaptive coronagraphy (DAC). The approach makes use of pixelated spatial light modulators (SLMs) in place of manufactured phase-mask focal-plane coronagraphs, taking advantage of the recent advances in this technology. Indeed, commercially-available SLM devices nowadays offer pixel sizes well below 10 um with fill-factor in excess of 90%, and some models now provide full phase-only modulation up to H-band at a framerate of 60Hz. In principle, this can make SLMs credible alternatives to fixed pre-manufactured phase masks for a range of chronographic configurations in the visible and near-infrared, opening an uncharted discovery space for adaptive coronagraphy.

Here we present a set of proof-of-principle experimental results obtained in the visible on our high-contrast imaging bench at ETH Zurich. First, we show that SLMs can be successfully implemented as focal-plane phase-mask coronagraphs for realistic instrumental F/#, delivering competitive peak-to-peak starlight rejection ratio beyond 1:100, hence meeting requirements set by typical on-sky Strehl ratios delivered by the current 2nd-generation AO systems. In practice, a variety of classical coronagraphic phase maps can be readily programmed into the SLM, like four-quadrants phase mask (FQPM), eight-octants phase mask (EOPM), and scalar vortex phase ramps with various topographic charges.

Second, we highlight a specific application where SLM-based adaptive coronagraphic might be particularly well suited, which is high-contrast imaging of multiple stars systems (binaries, triples, etc...). Indeed, we show that SLM phase maps can be readily re-programmed to simultaneously

null multiple point sources in the focal plane by carefully weighted superposition of coronagraphic phase patterns for a given target system, thus enabling to reach deep contrast inside a 360-degree field-of-view, whereas the regular static phase mask approaches would be adversely affected by the leakage of the stellar companion(s). To this purpose, we present comprehensive laboratory results exploring the parameter space covering the case of imaging binaries, in terms of separation, brightness ratio, pixel sampling at the SLM level, and geometry of the phase maps.

Finally, we attempt to broadly cover other applications where we think SLM-based adaptive coronagraphy may show great potential in the future, including wavefront sensing, optimized phase profiles for realistic telescope pupils, seeing- and aberration-matched real-time close-loop adaptive operations, synchronous detection, etc... We show corresponding preliminary proof-of-principle results, whenever already available.

9912-93, Session 17

Subwavelength grating vortex of charge 4 (SGV4): manufacturing assessment and performance analysis

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Vortex coronagraphs are instrumental solutions allowing high contrast direct imaging of exoplanets at small inner working angles, down to the diffraction limit of the telescope. These coronagraphs are composed of a focal-plane spiral-like phase mask, that can be made achromatic over large bandwidths by etching subwavelength gratings onto a synthetic diamond substrate. Over the past 3 years, several subwavelength grating vortex (SGV) phase masks, referred to as annular groove phase masks (AGPM), have been manufactured by our team (i.e. the VORTEX Project), validated on dedicated optical benches, and installed on 10m class ground-based telescopes (VLT/NACO, VLT/VISIR, LBT/LMIRCam, and Keck/NIRC2). More recently, we have proposed several original designs of next generation SGVs with higher topological charges (i.e. number of vortex phase revolutions). In this talk, we report on our latest development of an SGV4 (i.e. charge-4 vortex phase mask). We present our final design with minimized discontinuities and optimized phase ramp, and we show the results of our 3D rigorous numerical simulations using a finite-difference time-domain (FDTD) algorithm. We then show the results of our first manufacturing tests, using diamond-optimized microfabrication techniques such as reactive ion etching and nano-replication technique. Finally, we conclude with the performance analysis of our first prototypes based on surface profile metrology, as a prelude to laboratory tests on a dedicated coronagraphic testbed.

9912-94, Session 17

Precision optical edges for a starshade external occulter

John Steeves, Stefan R. Martin, Douglas Lisman, David R. Webb, Stuart B. Shaklan, Jet Propulsion Lab. (United States)

Starshades offer a method of performing high contrast imaging using space-based telescopes. The primary function of a starshade is to suppress light from a target star in order to image its orbiting planets. In order to provide the proper apodization function the edges of the starshade must follow a precise in-plane profile (accurate to < 50 μm RMS). However of equal importance is the issue of light from our own sun scattering off of the edges and entering the telescope. A method to alleviate this problem is to make the edges extremely sharp (< 1 μm radius) such that the area available for light-scattering is minimized. The combination of these two requirements, along with the need to integrate the edges into a 30-40 m dia. deployable structure, present a number of significant engineering challenges.

Substrate etching techniques are used to obtain the intended profile as well as the edge sharpness. Current efforts have implemented an isotropic etching process on thin metal substrates. With this technique a 1.0 m long substrate is patterned with the in-plane profile via photolithography techniques. The substrate is then immersed in an acidic solution and the material away from the photomask is removed in a near-isotropic fashion. This produces a “sickled” cross-section with a sharp terminal edge. Currently, amorphous metal substrates have been implemented due to their high elasticity, availability in thin sheet form, and absence of grain boundaries. However, high levels of internal stress inherent to the material have created a number of problems that ultimately reduce the quality of the edges across its entire length. Therefore, studies have been performed related to material selection, substrate thickness, and etching conditions in an effort to optimize the results of the etching process. Highly-directional etching techniques as well as post-manufacturing processes have also been explored and the advantages/challenges of each will be presented.

In addition to the initial manufacturing process, proper handling of the delicate edges during spacecraft assembly as well as survivability during launch are also of great concern. Prevention of damage during assembly is challenging as the edges are essentially unprotected optical elements. In addition, the variation in environmental conditions from the time of manufacture to the final launch date can result in a degradation of quality as a whole. Studies pertaining to edge durability and its effect on scattered light performance will be outlined. Techniques to mitigate damage before launch and upon orbit will also be presented.

Conference 9913: Software and Cyberinfrastructure for Astronomy IV

Sunday - Thursday 26–30 June 2016

Part of Proceedings of SPIE Vol. 9913 Software and Cyberinfrastructure for Astronomy III

9913-1, Session 1

SKA Telescope Manager (TM): status and architecture overview *(Invited Paper)*

Swaminathan Natarajan, Tata Consultancy Services, Ltd. (India); Yashwant Gupta, National Ctr. for Radio Astrophysics (India); Paul Swart, Gerhard Le Roux, SKA South Africa (South Africa); Alan Bridger, UK Astronomy Technology Ctr. (United Kingdom); Subhrojyoti R. Choudhury, Tata Consultancy Services, Ltd. (India); Mauro Dolci, Istituto Nazionale di Astrofisica (Italy); Domingos Barbosa, Instituto de Telecomunicações (Portugal); Lize Van den Heever, SKA South Africa (South Africa); Juan C. Guzman, Commonwealth Scientific and Industrial Research Organisation (Australia); Sonja Vrcic, NRC - Herzberg Astronomy & Astrophysics (Canada)

The Square Kilometer Array Radio Telescope project is building two telescopes, one each in Australia and South Africa. The Australian telescope, SKA-Low, will include hundreds of dipole array stations, while the South African telescope, SKA-Mid, includes over a hundred dishes with wideband single pixel feeds, and will incorporate the MeerKAT telescope currently under construction. Both telescopes will include pulsar search and pulsar timing capabilities. This is phase 1 of SKA: subsequent phases will expand the scale and baselines by a factor of 30-50, and possibly include additional telescopes and more receiver types.

A central feature of the project is the decision to maximize commonality among the telescopes. Accordingly, a key approach to development of the telescope management systems of the two telescopes is a common design, with limited variabilities, by a consortium from several countries, including India, South Africa, UK, Italy, Portugal, Canada and Australia. The project is currently in the design phase. A Preliminary Design Review of the architecture has been successfully completed, along with a rebaselining effort that re-scaled the SKA project to fit within available budget. The rebaselining included deferring a third proposed telescope (SKA Survey), resizing the two existing telescopes, and some significant feature changes. That such changes did not necessitate significant architectural changes to the Telescope Manager speaks to the success of the team's endeavour to create a generic specifications-driven radio telescope control and observations management architecture.

This paper will provide a status update on the control systems design effort, including the selection of the TANGO control systems framework and other technology choices. It will also discuss key challenges in the TM architecture, and our approaches to addressing them. The scale of the SKA, especially phase 2 which would expand it to thousands of receptors and baselines of thousands of kilometers, poses several challenges. This includes the need for high-levels of automated operation, creation of effective operator displays avoiding alarm floods and operator overload, dealing with faults and failed elements as a given during normal operations in a large system and allowing commissioning, integration and upgrades to co-exist with normal operations without disrupting it. The requirement to integrate precursors that are themselves currently under construction, accommodate heterogeneous receptor types and frequency bands, and support evolution during the 50-year observatory lifetime all necessitate a design that allows for monitoring and control of a heterogeneous and continuously evolving system.

We present our approach to addressing these challenges, including the adoption of a data-driven control systems architecture, standardized interfaces to system elements and the concept of Capabilities that facilitates resource management and scheduling. While this paper provides an architectural overview, other papers also submitted to this conference cover specific aspects, including the observation control system, challenges in observation management, the monitoring and control system design, self-management system and TM maintenance.

9913-2, Session 1

The software architecture to control the Cherenkov Telescope Array

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The Cherenkov Telescope Array (CTA) is an initiative to build two large arrays of Cherenkov gamma-ray telescopes. CTA will be deployed as two installations, one in the northern, and the other in the southern hemisphere, containing tens of telescopes of different sizes. CTA is a big step forward in the field of ground based gamma-ray astronomy, not only because of the expected scientific return, but also due to the order of magnitude larger scale of the instrument to be controlled. The performance requirements associated to such a large and distributed astronomical installation require a thoughtful analysis to determine the best software solutions.

The array control and data acquisition (ACTL) project within CTA will deliver the software to control and acquire the data from the CTA instrumentation. In this contribution we present the current status of the formal ACTL system decomposition in software building blocks, and the relationship between them. The system is modelled via the Systems Modeling Language (SysML) formalism. To cope with the complexity of the system, this architecture model is sub-divided into different perspectives. The relationships with the stakeholders and external systems are used to create the first perspective, the context of the ACTL software system. Use cases are used to describe the interaction of those external elements with the ACTL system, and are traced to a hierarchy of functionalities (abstract system functions) describing the internal structure of the ACTL system.

These functions are then traced to fully specified logical elements (software components), the deployment of which, as technical elements, is also described. This modelling approach allows us to decompose the ACTL software in elements to be created and the flow of information within the system, allowing a clear way to identify sub-system interdependencies. This architectural approach allows us to build the ACTL project model, linking requirements with deliverables as well as permitting the implementation of a flexible use-case driven software development approach thanks to the traceability from use cases to the logical software elements. The Alma Common Software (ACS) container/component framework, used for the control of Atacama Large Millimeter/submillimeter Array (ALMA) is the basis for the ACTL software, and as such it is considered as an integral part of the software architecture.

9913-3, Session 1

The transition from construction to operations on the ALMA control software

Ralph G. Marson, Rafael Hiriart, National Radio Astronomy Observatory (United States)

The Atacama Large Millimeter/Submillimeter Array (ALMA) is a set of 66 millimeter wave radio dishes high in the Andes in Northern Chile. All antennas are connected and operate as an interferometer making ALMA the most powerful millimeter telescope in the world. In 2013 ALMA was inaugurated and this formally marked the end of construction and the beginning of operations. This paper will focus on the impact, on the ALMA control software, of this transition from construction to operations.

The ALMA control software controls the hardware that does the observations. It reads an XML document, called a scheduling block, which contains a specification of an observation. This is interpreted by a hierarchy of software that converts this specification to a set of scans, adds any missing calibrations & determines what calibrators are most suitable. The scans are scheduled to It then sends detailed commands, at just the right time, to all the relevant pieces of hardware, including the correlator, front-end & antennas. There are around 100 separate computers, most of them running a real-time operating system, that work as one system to ensure that suitable astronomical data, and all necessary meta-data, is sent to the archive for use by the data reduction software.

During the construction period, of over ten years, the ALMA control software was a crucial piece of all ALMA activity. Any tests that needed control of more than one piece of hardware and could not be done in a lab required the coordination of the ALMA control software. Numerous "throwaway" bits of software were produced for various specialized purposes. The emphasis was not on writing the software to support science observations but on supporting the commissioning tests and software to check that the hardware was meeting specifications. Because the software to support science observations could not be ignored there frequently were conflicting demands on the control software team. Important priorities often took second place to the urgent ones.

The transition to operations over the last few years has seen a significant change in the activities of the ALMA control software team. While the software is no less crucial there is an increased emphasis on efficiency and robustness and a corresponding de-emphasis on new features. Many of the bits of commissioning software are being discarded as there is insufficient staff and inadequate justification to support all the software that was produced during construction. The core software is being consolidated into a more maintainable product that can efficiently be supported and flexibly evolved over the next few decades.

9913-4, Session 1

The growth of complexity in the evolution of control systems for ESO telescopes and instruments

Mario J. Kiekebusch, Gianluca Chiozzi, Christian Lucuix, Krister Wirenstrand, European Southern Observatory (Germany)

ESO continuously extends and improves the observation capabilities of its observatories by developing further its telescopes and its instrumentation programme. Every new generation of instruments, starting from the early instruments on the La Silla telescopes and going to the instruments being designed for the E-ELT is more sophisticated than the previous one. Several generations of instruments are overlapping now on the VLT/VLTI telescopes with new ones under development. In comparison with first generations, new instruments need to control larger and faster detectors, implement more complex acquisition sequences and a larger number of observation templates, control a bigger number of motorized opto-mechanical functions, have superior cryogenic control capabilities, as well as handle increased requirements on reliability. However, the growing complexity is reflected not only on the scale of the involved control systems but also in the nature of modern control techniques such as fringe tracking or adaptive optics systems, which are required to run at high frequencies with many interdependencies, in order to achieve diffraction limited observations.

This growth in structural and functional complexity of the control systems has been managed at ESO with the introduction of state of the art solutions in different engineering disciplines such as electronics, control and software. At the same time, ESO has been able to reduce the impact of implementing more complex systems and to keep uniformity across the observatories by integrating the new solutions into existing frameworks, and by improving and extending them.

In this paper we will use our privileged possibility of accessing specifications, design and implementation of the control system for more than 30 instruments and several generations of telescope control systems in a time span of 50 years, developed following a coherent and consistent plan. This paper will analyse several aspects in the evolution of the control systems throughout the different generations and it will try to compare their complexity and the solutions adopted to facilitate the task of implementing more complex control systems. We will try to give an historical perspective and to look forward at the challenges for the coming control systems of E-ELT generations.

9913-6, Session 2

The active surface control system for the Tian Ma Telescope

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The Tian Ma Telescope (TM) is the largest fully steerable radio telescope in Asia. It has a primary reflector of 65-m in diameter with a shaped Cassegrain configuration. The first-developed large active surface system made a breakthrough in China. Some key technologies have been successfully solved during the development process in the following: 1) Development of high-precision, high-reliability and long-life actuators; 2?Thousands of points real-time, distributed, high reliability monitoring and collaborative control can achieve the real-time distributed monitoring of 1104 actuators. In this paper we will describe the the active surface control system at the TM Telescope including control of the metrology systems, the actuator systems. We will also describe the design and implementation of the software and hardware for the active surface control system.

9913-7, Session 2

Computer-aided star pattern recognition with astrometry.net: in-flight support of telescope operations on SOFIA

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Ames Research Ctr. (Germany); Alfred Krabbe, Deutsches SOFIA Institut (Germany)

SOFIA is an airborne observatory, operating a 2.7 m telescope on-board a modified Boeing 747SP. When SOFIA opens its door to the night sky, the initial telescope pointing is estimated from the aircraft's position and heading as well as the orientation of the telescope relative to the airplane. To be accurate, this estimate has to be calibrated with images from the sky.

SOFIA has three guidance cameras (WFI, FFI, FPI) with complementing field of views (6°, 1°, 0.13°) that provide image data to solve this task. The telescope operator (TO) has to recognize a number of catalog stars in these pictures by eye, mark them in the pictures by drawing boxes on an image overlay, and select the corresponding catalog identifier from a drop down menu. This allows a correlation of image data with catalog data to determine field rotation, right ascension and declination of the telescope, and to calibrate the telescope pointing accordingly.

Even with lots of training and experience, manual pattern recognition is time consuming. Every time the heading of the aircraft changes for another observation in a different part of the sky, the telescope operator has to check and calibrate the telescope pointing again. Although an inertial measurement is provided by laser-based gyroscopes, continuous centroid measurements of guide stars are required to compensate their drift. During periods without optical guiding, this drift deteriorates the telescope pointing estimate.

Manual pattern recognition can be especially difficult in sparse or dense star fields. As computer-aided star pattern recognition is standard practice in astrometric data reduction, we were looking for a tool that supports the TO with this task. This could potentially save some valuable minutes on every SOFIA flight in favor of collecting more science data, further increasing the efficiency of the observatory.

The astrometry.net package appears to be the ideal solution as it provides a very robust, reliable and fast algorithm for blind astrometric calibration of images. It does not require any a-priori information or an initial coordinate guess which simplifies integration. It was developed on Linux and is free open source software. We extensively tested the package with image data from various ground-based and airborne observations as well as data from all three SOFIA guiding cameras. The algorithm showed an exceptional robustness against all kinds of image artefacts and calculated not a single false positive.

We report about the integration of the astrometry.net package on the TO workstations on SOFIA that are running Solaris 10. SOFIA's wide field imager (WFI) is typically running at integration times of 2.5-3.0 s. Our tests show that WFI images can be solved faster than that, which allows us to display an almost instant, continuous feedback of right ascension, declination and rotation angle values on the TO GUI that are calculated from the stream of WFI images. This information can be used to correct telescope pointing errors instantly. We conclude with an outlook on other possible use cases.

9913-8, Session 2

Control and monitoring software for the Greenland Telescope

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The Greenland telescope (GLT) is 12 meter diameter ALMA prototype antenna that was awarded to the Smithsonian Astrophysical Observatory (SAO) by the National Science Foundation (NSF) in 2011. SAO and Academia Sinica Institute of Astronomy and Astrophysics, Taiwan, are working together to retrofit and relocate this antenna near the NSF Summit station in Greenland, to establish an observatory for submillimeter wavelength VLBI and single-dish astronomy approaching THz frequencies. We present the current status of the antenna control and monitoring software for the GLT. The primary goal of this software is to provide an efficient and reliable interface to the lower level software provided by the vendors of the primary antenna and secondary hexapod drive systems. This higher level software also performs the astronomical calculations for single-dish and VLBI observations, and supports special modes for antenna testing such as pointing calibration and holography mapping.

The initial version of this software was tested on the prototype antenna at the NRAO JVLA site near Socorro, New Mexico, in 2011-2012.

This version conforms with the ALMA system, including a heartbeat pulse for timing synchronization of every command, and CAN-bus communication with the Antenna Control Unit (ACU). The antenna's drive system required significant refurbishing and retrofitting for operation in the cold temperature (mean: -30 C) at Greenland. Several new components are installed: drive system motors, gearboxes, encoders, tiltmeters, limit switches and ACU, by Vertex Antennentechnik in Germany. The subreflector hexapod is a new system built by ADS International, in Italy. The revised higher-level software uses Ethernet instead of CAN-bus for communication with the low-level control systems, but we have retained the timing synchronization and CAN-bus as an option, for compatibility in future, to support the use of an ALMA receiver on the GLT. Although there will be on-site telescope operators at the GLT, remote operation and monitoring, over a low-bandwidth network connection, is one of the significant requirements for the software.

Parts of the control the new control software were tested at Vertex and ADS, during factory acceptance tests of the new servo system and the new subreflector hexapod unit, in 2014-2015. The antenna will be deployed at the Thule US Air Force Base in Greenland, in the summer of 2016. The higher-level control and monitoring software is coded in C and Python, and is adopted from the software developed for the Submillimeter Array. The scope of the software described here, is to provide control and monitoring support for initial testing and commissioning of the antenna in Thule, and also carry out VLBI observations. We will also outline the future development of the software, as the project evolves with the installation of various receivers and backend instrumentation, for the next phase of operation at the Summit station in Greenland, anticipated in 2019.

9913-9, Session 2

LSST control software component design

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Construction of the Large Synoptic Survey Telescope system involves several different organizations, a situation that poses many challenges at the time of the software integration of the components. To ensure commonality for the purposes of usability, maintainability, and robustness, the LSST software teams have agreed to the following for system software components: a summary state machine, a manner of managing settings, a flexible solution to specify controller-controllee relationships reliably as needed, and a paradigm for responding to and communicating alarms. This paper describes these agreed solutions and the factors that motivated these.

9913-106, Session 2

Improving the pointing and tracking performance of the Keck telescopes

Shui Hung Kwok, James E. Lyke, Kevin Tsubota, Kevin L. McCann, Tomas Krasuski, Jeffrey A. Mader, W. M. Keck Observatory (United States)

Pointing and tracking performance is one of the key metrics that characterize a telescope's overall efficiency. The pointing performance of the Keck telescopes has been surpassed by newer large telescopes due to the use of rotary friction encoders to provide position feedback to the control system. While poor tracking can be compensated by guiding, poor blind pointing performance can lead to loss of observing time.

In this paper we present a history of the efforts to reduce the impact of poor pointing, as well as the improvements achieved after the installation of new tape encoders. We will discuss the calibration and testing methods and the tools for monitoring and maintaining the desired pointing performance. A comparative analysis of the pointing performance before and after the telescope control system upgrade will also be presented.

9913-10, Session 3

An automated qualification framework for the MeerKAT CAM (Control-And-Monitoring) system

Lize Van den Heever, SKA South Africa (South Africa)

The MeerKAT 64-dish radio telescope is currently in full production in South Africa's Karoo region. This paper introduces an Automated Qualification Framework that was developed for the formal Qualification Testing of the Control-And-Monitoring (CAM) subsystem of MeerKAT. It discusses the approach and implementation and lastly reports on the lessons learnt and benefits.

The goal of the Automated Qualification Framework (AQF) was to perform as much as possible of the formal CAM Qualification Testing through automating the integrated CAM tests, automating the evaluation, capturing the results, and automatically producing the test procedures and test results documents. The integrated CAM tests are run daily through a Jenkins continuous integration server on a fully simulated MeerKAT CAM system, producing the qualification test result as a test artifact.

The AQF allows each Integrated CAM Test to reference the MeerKAT CAM requirement it covers and automatically produces the Qualification Test Procedure and Qualification Test Report from the test steps and evaluation steps coded in the test. The AQF uses an export of the CORE requirements model of MeerKAT to produce a cross-verification matrix of the test results against the CAM requirements. Peer reviews are performed on each Integrated CAM Test as as a quality assurance step to ensure the test actually performs the steps and checks as claimed in the AQF steps.

The AQF is implemented as a nosetest plugin that allows a developer of each Integrated CAM Test to specify the CAM requirement that is covered by the test, to define the test steps to be performed and the verification steps to evaluate the test results.

To test that a critical alarm is raised when a fire is detected, the test will reference with the appropriate requirement number, will trigger the fire sensor, will check that the alarm is detected, will check that the alarm level is critical and is logged, will then reset the fire sensor.

A second DEMO test for Qualification Demonstration then only verifies the display of the alarm to the operators.

The CAM Acceptance Testing on site against the actual MeerKAT deployed subsystems also makes use of the AQF by developing automated tests specifically for site Acceptance Testing and also by tagging applicable qualification tests as acceptance tests (those that can be run on the real system like antenna pointing tests vs those that can't like veritying the shutdown procedure after simulating a cooling failure in the processing building).

A first version of the AQF was used for Timescale A Qualification of MeerKAT CAM as demonstration to the System Engineers for MeerKAT and the AQF was fully implemented and used for the second development iteration for Timescale B Qualification of MeerKAT CAM. The MeerKAT System Engineers are extremely happy with the AQF results, but mostly by the approach and process it enforces. Although it took time to develop and mature the AQF (and it is an ongoing effort as it can always be improved further) and it is a "real mission" sometimes to keep developing and updating the Integrated CAM Tests as implementation details changes and new functionality is added, the benefits of having this Automated Qualificaiton Framework far out-weighs the resource commitment. And in the long run may not take much more resources than it would to "manually" test and find the problems.

9913-11, Session 3

Rules of thumb to increase the software quality through testing

Marco Buttu, INAF - Osservatorio Astronomico di Cagliari (Italy); Marco Bartolini, Carlo Migoni, Andrea Orlati, Sergio Poppi, Simona Righini, INAF - Istituto di Radioastronomia (Italy)

The software maintenance typically requires 40-80% of all project costs, and this considerable variability mostly depends on the software internal quality: the more the software is designed and implemented to constantly welcome new changes, the lower will be the maintenance costs. The internal quality is typically enforced through testing, which in turn also affects the development and maintenance costs. This is the reason why testing methodologies have become a major concern for any company that builds or is involved in building software.

Although there is no testing approach that suits all contexts, we infer some general guidelines learned during the Development of the Italian Single-dish COntrol System (DISCOS), which is a project aimed to produce the control software for the three INAF radio telescopes (the Medicina and Noto dishes, and the newly-built SRT). These guidelines concern both the development and the maintenance phases, and their ultimate goal is to maximize the DISCOS software quality through a Behavior-Driven Development (BDD) workflow beside a continuous deployment pipeline.

We consider different topics and patterns; they involve the proper apportion of the tests (from end-to-end to low-level tests), the choice between hardware simulators and mockers, why and how to apply TDD and dependency injection to increase the test coverage, the emerging technologies available for test isolation, bug fixing, how to protect the system from the external resources changes (firmware updating, hardware substitution, etc.) and, eventually, how to accomplish BDD starting from functional tests and going through integration and unit tests.

We discuss pros and cons of each solution and point out the motivations of our choices either as a general rule or narrowed in the context of the DISCOS project.

9913-12, Session 3

Behavior driven testing in ALMA telescope calibration software

Juan Pablo Gil, Mario Garces, Tzu-Chiang Shen, ALMA (Chile); Dominique Broguière, Institut de Radio Astronomie Millimétrique (France)

ALMA observatory has reached its operational stage in 2013, but its software is still under active development, which implements new capabilities to be offered to the scientific community. The current software release process involves the delivery of short releases that includes a set of new features for one or more subsystems of ALMA Software. Also, the testing stage of the same process involves not only developers and testers, but also stakeholders (i.e: scientists and engineers). Currently, there are still some drawbacks in the used testing methodology. One of the most relevant problem is that most software subsystems relies on functional tests that are executed either by exploratory analysis or by custom scripts. As a consequence, the current methodology produce a knowledge gap between developers, testers and scientist in the sense of comprehension and/or repeatability of testing results. In that way, Behavior Driven Development (BDD) was proposed in order to increase test formalisation and automation of testing activities. BDD is an agile technique derived from Test Driven Development that encourages communication between roles by defining and automating test cases using natural language. In BDD, each requirement is translated into several test cases (scenarios) that covers the correctness of the requirement functionality. In addition, the use of natural language within test cases definition allows participants to develop a common domain language and to perform, in advance, peer reviews to assure correctness of the defined testing strategy for a specific release. The selected subsystem for this first experience was Telescope Calibration (TELCAL), which objective is to produce a set of calibration data in near real-time by the observations. Regarding TELCAL OFFLINE version (instead of its ONLINE version), results can be reproducible by using an input dataset. These characteristics make this subsystem a perfect candidate for BDD approach. This paper describes how we have implemented and maintained test cases to verify TELCAL based on BDD, the infrastructure needed to support them and explore mechanism to expand this technique to other subsystems, in particular to online parts of the TELCAL subsystem that interact with real time observing processes.

9913-13, Session 3

The evolution of the simulation environment in the ALMA Observatory

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The Atacama Large Millimeter /submillimeter Array (ALMA) will be a unique research instrument composed of 66 reconfigurable high-precision antennas, located at the Chajnantor plain in the Chilean Andes at an elevation of 5000 m.The observatory has entered into operation phase since 2014. This transition changed the priorities within the observatory, in which, most of the available time will be dedicated to science observations at the expense of technical time that software testing used to have available in abundance (since software/hardware integration was the former priority during construction phase)

The scarcity of the technical time surfaces one of the weakest points in the existent infrastructure available for software testing: the simulation environment of the ALMA software. In ALMA, simulation capabilities were initially developed to satisfy Control and Correlator subsystem needs, supplying them with virtual hardware devices to interface with the software components being developed. Additional simulation layers and capabilities were added during the years by different teams, but they were focused on the functionality aspect but not on the real operation scenarios with all the antennas. Therefore, scalability and performance problems introduced by new features or hidden in the current accepted software cannot be verified until the actual problem explodes during operation. The lack of a representative testing environment will seriously impact the efficiency of the ALMA incremental software release process.

Therefore, it was planned to design and implement a new simulation environment, which must be comparable - or at least- be representative of the production environment. Duplicating the production environment was not an option, since it would be prohibitive from the point of view of the associated cost. Adjustments in the existent production architecture had to be introduced, but with special care on keeping the simulation environment comparable in term of CPU load, network bandwidth throughput, memory usage and software configurations. The selected platform to provide computing power is based on blade technology of Cisco Unify Computing System (UCS). Concepts of model in the loop (MIL) and hardware in the loop (HIL) were explored to allow that the application code deployed in the simulation environment is the same as the one deployed in the production environment.

The new simulation platform will provide the required amount of time for testing purposes, which includes verification of new features, fixes of detected bugs and long term stability and scalability of the system, at same time it allows us to maximize the efficiency of the reduced technical time available in the production environment, which will be dedicated only for the final validation of a release and small set of features that interact directly with hardware.

In this paper we will review experiences gained and lessons learnt during the design and implementation of a full simulated environment.

9913-14, Session 3

Modernized build and test infrastructure for control software at ESO: highly flexible building, testing, and automatic quality practices for telescope control software

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An automatic and reliable build and test system is a basic prerequisite for the success of every modern software project. Modifications made by developers need to be included into the system, integrated and verified as soon as possible. This is even more the case when the software has to be deployed on systems for which downtime is a critical factor like ESO's telescopes and instruments.

In this context from a long time, the control software engineers at ESO have been very eager to adopt automatic procedures for building, testing and integrating with an in-house software solution named NRI (Nightly Report Infrastructure). The in-house solution was created at a time when there were not many common off-the-shelf products of this type and it has accomplished its duties successfully for many years. Its operations and interface were highly customized to the project's needs, but on the negative side the solution was not very scalable and required often important code changes to be maintained and to accommodate new upcoming requests. Therefore, after an internal investigation for a more versatile solution, in the last year the control software infrastructure at ESO migrated to an open-source solution, Jenkins CI, which provides an improved distributed and cross-platform infrastructure for highly parallelized builds and tests for most of the projects managed.

The paper will present common building and testing infrastructure concepts, the previous solution used at ESO and the migration to the new infrastructure, showing the big improvements made in terms of reduced overall execution time, parallel testing on different versions and architectures and higher reproducibility of testing conditions. Keeping

impact on the developer at a minimum by reproducing to a very high degree the features of the user interface of the previous solution was also of primary importance. Additionally the new infrastructure improves also automatic execution of quality assurance tools, such as static code checking tools, code coverage analysis and memory and system resources leakages and leverages on practices such as using automatic virtual machines management and Linux containers for test environment reproducibility. Builds and tests are carried out with various patterns: on-commit continuous-integration style, on user demand and nightly or weekly scheduling, all this in an environment with many internal developers but also external developers from Consortia or contractors. Results are available and archived via Web, but problem notifications are sent immediately to developers and managers. The results include a variety of system logs and debugging information that should immediately point the developer into the right direction in the debugging session. Intermediate build results are also stored and new versions of software can be packed and deployed automatically to different machines. Automatically generated documentation is also immediately prepared and published alongside the binaries.

Many good practices had to be enforced in the development cycle to achieve the full potential of the infrastructure: patterns of usage of the code repository, SVN in our case, build system, such as modularized and parallelizable GNU make recipes, and test scripts, written so they incorporate as little information on the context they will be executed in. External shared resources access has to be carefully managed with locking mechanisms and with interfaces to an extensible booking system. Hardware resources are managed at power level via network driven power switches to maximize their uptime even in case of low level failure blocking their functionalities. The transition to the new system proved to be quite cheaper time-wise than previously expected, original effort estimation being one of the motivations that the transition was postponed, and there was practically no need for additional training for users given the similarity to the previous system and ease of use of the new interface .

The usage of the new infrastructure for the VLT and SPARTA based adaptive optic systems will be described in detail. The infrastructure is also prepared to host the new EELT project that poses very important new challenges such as a wider variety of architectures, programming languages and operating systems to be supported. Currently for EELT internal prototypes have been added and the first code modules should be integrated in 2016.

9913-16, Session 4

Investigating interoperability of the LSST data management software stack with Astropy

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The Large Synoptic Survey Telescope will be an 8.4m optical survey telescope sited in Chile and capable of imaging the entire sky twice a week. The data rate of approximately 15 TB per night and the requirements to both issue alerts on transient sources within 60 seconds of observing and also to create annual data releases means that automated data management systems and data processing pipelines are a key deliverable of the LSST construction project. The LSST data management software has been in development since 2004 and, like other software developed in that era such as CASA, is based on a C++ core with a Python control layer. The software consists of nearly quarter of a million lines of code covering the system from fundamental WCS and table libraries to pipeline environments and distributed process execution.

The Astropy project began in 2011 as an attempt to bring together disparate open source Python projects and build a core standard infrastructure that can be used by and built upon by the astronomy community. This project has been phenomenally successful in the years since it has begun and has grown to be the de facto standard for Python software in astronomy. Astropy brings with it considerable expectations from the community on how astronomy Python software should be developed and it is clear that by the time LSST is fully operational in the 2020s many of the prospective users of the LSST software stack will assume that Astropy software will be integrated.

In this paper we will describe the overlap between the LSST science pipeline software and Astropy software and investigate areas where the LSST software provides new functionality. We will also discuss the possibilities of re-engineering the LSST science pipeline software to build upon Astropy, including the option of contributing affiliated packages.

9913-17, Session 4

VIALACTEA knowledge base: homogenizing access to Milky Way data

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The EU-FP7 funded project VIALACTEA has a work package dedicated to “Tools and Infrastructure” (WP5) among whose tasks task 1 is named “Database and Virtual Observatory Infrastructure”.

This task aims at providing an infrastructure to store all the resources needed by the, more purposely, scientific work packages of the project itself.

This infrastructure includes a combination of: storage facilities, relational databases and web services on top of them, and has taken, as a whole, the name of VIALACTEA Knowledge Base (VLKB).

The storage part of the VLKB simply holds all of the observational data files (FITS format data multi dimensional cubes and 2D images, grouped by survey means) required by the VIALACTEA community as the input information for scientific production. It consists of about 20 surveys (if considering the single species and transitions investigated) of galactic plane radio observations in form of FITS cubes with a 3rd axis dedicated to velocity spectra, and about 15 2D image surveys in the radio continuum. All of them form a collection of about 14000 datasets.

The VLKB database is the content holder for both the metadata of the stored files and data resources themselves in terms of catalogues of compact or diffuse objects.

The database part consisting of FITS collection metadata part is used by the discovery and access services.

The data part, consisting of catalogues, completes the input base for scientific exploitation.

Part of these catalogues consists of some FITS files processing (of selected surveys).

These catalogues are also output of the scientific work of the project; they consist of: compact sources identified in single radio bands (of the above surveys) and then combined into a band merged catalogue with all the multi band SED information connected together, filamentary and bubble like diffused structures, computational SED models, velocity peak information to compute distance estimation of sources.

The VLKB database, metadata and data, is also the information resource on top of which an IVOA TAP service has been attached to let the VIALACTEA community users integrate their data with the VO available resources outside the project (i.e. without the need to download and reload data files each time they need to cross correletae information).

Alongside the TAP service a set of services to allow discovery, retrieval and cutout of the available data cubes and images has been provided, to answer the explicit request for positional and velocity range searches and cut on the provided radio surveys of the galactic plane.

These latter services make use of the WCS information of the FITS to perform discovery and cutout on such a dishomogeneous collection of datasets and its design is inspired by the IVOA discovery, cutout and access protocols.

This contribution illustrates the current status of the infrastructure. It details the set of resources put together to serve as the actual data resources; describes the database that allows data discovery through VO inspired metadata mainteinance; illustrates the discovery, cutout and access services built on top of the former two for the users to exploit the data content.

9913-18, Session 4

A case study in adaptable and reusable infrastructure at the Keck Observatory Archive: VO interfaces, moving targets, and more

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The Keck Observatory Archive (KOA) (https://koa.ipac.caltech.edu) curates all observations acquired at the W. M. Keck Observatory (WMKO) since it began operations in 1994, including data from eight active instruments and two decommissioned instruments. The archive is a collaboration between WMKO and the NASA Exoplanet Science Institute (NExScI). Since its inception in 2004, the science information system used at KOA has adopted an architectural approach that emphasizes software re-use and adaptability. This paper describes how KOA is currently leveraging and extending open source software components to develop new services and to support delivery of a complete set of instrument metadata, which will enable more sophisticated and extensive queries than currently possible. We plan to post all the code described below on GitHub by Summer 2016.

In August 2015, KOA deployed a program interface to discover public data from all instruments equipped with an imaging mode. The interface complies with version 2 of the Simple Imaging Access Protocol (SIAP), under development by the International Virtual Observatory Alliance (IVOA), which defines a standard mechanism for discovering images through spatial queries. The heart of the KOA service is an R-tree based database-indexing mechanism prototyped by the Virtual Astronomical Observatory (VAO) and further developed by the Montage Image Mosaic project to provide fast access to large imaging datasets, as a first step in creating wide-area image mosaics (such as mosaics of subsets of the 4.7 million images of the SDSS DR9 release). The KOA service uses wrappers around existing modules to query an SQLite database that references the indices and returns results to the user. The service uses a JSON configuration file to describe the association between instrument parameters and the service query parameters and so make it applicable beyond the Keck instruments.

The images generated at the Keck telescope usually do not encode the image footprints as WCS fields in the FITS file headers. Because SIAP searches are spatial, much of the effort in developing the program interface involved processing the instrument and telescope parameters to understand how accurately we can derive the WCS information for each instrument. This knowledge is now being fed back into the KOA databases as part of a program to include complete metadata information for all imaging observations.

The R-tree program was itself extended to support temporal and spatial indexing, in response to requests from the planetary science community for a search engine to discover observations of Solar System objects. With this 4D-indexing scheme, the service performs very fast time and spatial matches between the target ephemerides, obtained from the JPL SPICE service. Our experiments indicate that these matches can be more than x100 faster than when separating temporal and spatial searches. Images of the tracks of the moving targets, overlaid with the image footprints, are computed with a new command-line visualization tool, mViewer, released with the Montage distribution. The service is currently in test and will be released in Spring 2016.

9913-134, Session 4

High-contrast imaging in the cloud

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Astronomical data sets are growing ever larger, and the area of high contrast imaging of exoplanets is no exception. With the advent of fast, low-noise detectors operating on the orders of 10 to 1000 Hz, huge numbers of images can be taken during a single hours-long observation. High frame rates offer several advantages, such as improved registration and jitter rejection, frame selection, and potentially significant gains in speckle calibration using temporal information. However, applying advanced image processing algorithms to such large data sets is computationally challenging. Here we describe a cloud-based data reduction system developed for the Magellan AO VisAO camera, which is capable of processing tens of thousands of images at a time. We demonstrate these capabilities with several large visible-wavelength high contrast data sets of the exoplanet host star beta Pictoris. Finally, we describe our prototype system for storing, transporting, and distributing such large data sets from a remote site in Chile.

9913-19, Session 5

The astronomer, the software engineer, and the cloud *(Invited Paper)*

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We are in the midst of a transition in the way that computing resources are obtained in the sciences. Cloud-based architectures play an increasing role in scientific processing as well as scientific communication, leveraging the considerable technical investment in these platforms. Typically astronomers have believed that the economics drive them away from this model, however these calculations often fall short of the total cost of delivering computing infrastructure. Moreover there is a often a false dichotomy between commercial cloud services (like Amazon Web Services) and traditional bare-metal "special snowflake" hardware; privately deployed clouds (such as university OpenStack clusters) represent a path forward with many of the technological advantages of

working in an open standardized infrastructure while avoiding some of the direct costs of the commercial clouds. Here we describe how we have navigated some of these issues in the context of engineering the LSST Data Management's developer infrastructure, which includes a cross-platform cloud-based continuous integration architecture.

9913-20, Session 5

A cyber infrastructure for the SKA Telescope manager

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The Square Kilometre Array Telescope Manager (SKA TM) will be responsible for the SKA Operations and Observation Management, carrying out System diagnosis and collecting Monitoring & Control data from the SKA sub-systems and components. To provide adequate compute resources, scalability, operation continuity and high availability, as well as strict Quality of Service, the TM cyber-infrastructure (embodied in the Local Infrastructure - LINFRA) consists of COTS hardware and infrastructural software (for example: server monitoring software, host operating system, virtualization software, device firmware), providing a specially tailored Infrastructure as a Service (IaaS) and Platform as a Service (PaaS) solution. The TM infrastructure provides services in the form of computational power, software defined networking, power, storage abstractions, and high level, state of the art IaaS and PaaS management interfaces.

This cyber platform will be tailored to each of the two SKA Phase 1 telescopes (SKA-MID in South Africa and SKA_LOW in Australia) instances, each presenting different computational and storage infrastructures and conditioned by location. This cyber platform will provide a compute model enabling TM to manage the deployment and execution of its multiple sub-components (observation scheduler, proposal submission tools, etc). In this sense, LINFRA is primarily focused towards the provision of isolated instances, mostly resorting to virtualization technologies, while defaulting to bare hardware if specifically required due to performance, security, availability, or other requirement. Under this assumption, TM executes sub-elements components in instances that can be deployed, migrated, replicated and upgraded, while providing key performance indicators regarding the execution conditions of each execution instance created. The deployment functionality enables the easy deployment of instances from development into production environments. The Migration functionality enables the instances to be moved between physical hardware resources in order to increase availability and redundancy. The Replication functionality enables redundancy and automatic scaling to cope with bursts of requests. The Upgradability functionality enables components to be replaced by updated versions with fixes or new features. For each instance, key operational parameters will be reported, allowing the SKA TM to track the correct execution condition of its components and maintaining high operational availability.

In this paper, we describe the basic tools and building blocks of the compute and virtualization technologies constituting the tailored IaaS and PaaS service to the SKA Telescope Manager.

9913-22, Session 5

The AST3 controlling and operating software suite for automatic sky survey

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Because of both the extreme environment in Antarctica and a whole year unattended operation, the controlling and operating hardware system of AST3 must be highly customized compared with ground-based telescopes in other observatories. As a consequence, the controlling and operating software system must also be highly specialized and ast3suite was thus designed to run AST3 remotely and robotically. In order to make the software system be modular and suitable for both remote command-line based test and automatic observation, ast3suite is designed to be composed of three parts: daemon servers, basic commands, and survey script. The daemons are those programs running constantly in background when the host operating system starts. They directly communicate with various devices of AST3's hardware system and provide services to their clients. The basic commands are actually the client programs of these daemons. They send requests to the daemons and ask them to operate on certain devices. After the daemons finish requests, the client programs fetch results back and usually print them to standard output and/or log files. If logic flow allows, the daemons should be moderately concurrent. The same client processes can simultaneously send requests to a daemon. Since the clients indirectly operate on devices, there are no resource race conditions. Such a server/client architecture adopted in ast3suite makes our software system very consistent and reliable. The communication between daemons and clients is via TCP/IP, so that ast3suite also has capability to do synchronous observations of a telescope array in the future. The survey script executes the basic commands sequentially in a loop to achieve automatic sky survey. Ast3suite was deployed on the real hardware system of AST3 and had been carefully tested in Mohe for five months before it was actually used at Dome A in 2015. The test and running results, including running logs and saved images, show that ast3suite accommodates to robotic telescope in Antarctica and has the potential to be gerneralized for broad use.

9913-23, Session 5

Thirty Meter Telescope common software update

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The TMT Software System consists of software components that interact with one another through a software infrastructure called TMT Common Software (CSW). CSW consists of software services and library code that is used by developers to create the subsystems and components that participate in the software system. CSW also defines the types of components that can be constructed and their functional roles in the software system.

TMT CSW has recently passed its preliminary design review. The unique features of CSW include its use of multiple, open-source products as the basis for services, and an approach that works to reduce the amount of CSW-provided infrastructure code. Considerable prototyping was completed during this phase to mitigate risk with results that demonstrate the validity of this design approach and the selected service implementation products. This paper describes the latest design of TMT CSW, key features, and results from the prototyping effort.

The core of CSW is implemented on the JVM in the Scala programming language with both Java and Scala programming interfaces. The CSW

programming environment is based on the Akka distributed application library. The source code CSW is open source and available on Github.

9913-24, Session 5

DDS as middleware of the Southern African Large Telescope control system

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The Southern African Large Telescope (SALT) software control system is realised as a distributed control system, implemented predominantly in National Instruments' LabVIEW. Communication between the telescope control subsystems employs a cyclic publish-subscribe, state-based message-passing architecture. Transmitting a message is accomplished by performing an HTTP PUT request to a WebDAV directory on a centralised Apache web server; receiving involves polling the web server for new messages. While the method is simple and lightweight, it contains a number of weaknesses; a scalable distributed communication solution with minimal overhead is a better fit for control systems.

This paper describes our exploration of the Data Distribution Service (DDS) as middleware for SALT. DDS is a formal standard specification, defined by the Object Management Group (OMG) that presents a data-centric publish-subscribe model for distributed application communication and integration. It provides an infrastructure for platform-independent many-to-many communication.

A number of vendors provide implementations of the DDS standard; RTI, in particular, provides a DDS toolkit for LabVIEW. We have evaluated this toolkit against the needs of SALT, and have identified a few deficiencies, particularly when bearing in mind backward compatibility with the existing architecture. The most important aspect is that data elements of the toolkit messages are not dynamically resizable: the data elements have to be pre-declared to be of a particular maximum size, that cannot be increased at run-time. To overcome this restriction we have developed our own implementation that interfaces LabVIEW to DDS.

Our LabVIEW DDS interface implementation is built against the RTI DDS core component, provided by RTI under their Open Community Source licence. The wide variety of platforms we use at SALT dictate that the interface implementation be platform independent. Since RTI provides access to the RTI DDS core source code, we are able to build the required software libraries for all of the platforms on which we require support.

The communications functionality of our implementation is based on UDP multicasting. Multicasting is an efficient communications mechanism with low overheads, which avoids the duplication of point-to-point data transmission on a network where there are multiple recipients of a particular item of data.

We present a performance evaluation of DDS against the current HTTP based implementation with a discussion on specific optimisations developed for the Prime Focus Guidance System Upgrade project. We also discuss the lessons learnt and describe planned future work.

9913-128, Session 5

The NOAO data lab: science-driven development

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We are developing the [it]NOAO Data Lab[it] to provide the infrastructure needed to maximize community use of the high-value survey datasets now being collected with NOAO telescopes and instruments, in particular the Dark Energy Camera. The Data Lab will allow users to access and search databases containing large catalogs, visualize, analyze, and store the results of these searches, combine search results with data from other archives or facilities, and share these results with collaborators through a central workspace or publication service. In the process of implementing the needed services, we are using specific science cases to guide development of the system framework and tools. The result is a Year-1 capability demonstration that implements nearly all of the major software components in the context of a functioning science use case.

The science case used for developing this demonstration is a search for faint Milky Way satellite galaxies, using the Data Lab infrastructure to show how one can search for dwarfs across increasingly larger sets of data. We begin this demonstration using an interactive approach to reproduce the discovery of the Hydra II dwarf [Martin et al, 2015] in the SMASH [Nidever et al, 2013] survey catalog. Next, we expand the search using a scripted approach incorporating the same techniques to examine other SMASH target fields and large-area surveys. Finally, we demonstrate a search for dwarfs starting with image data publicly available from the NOAO Science Archive, processing the images through a quick-look photometric pipeline, and filtering the resulting catalogs.

9913-25, Session 6

The readout and instrument control system of the Dark Energy Spectroscopic Instrument (DESI)

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DESI, the dark energy spectroscopic instrument, is a fiber-fed multi-object spectrograph currently under constructions. DESI will be installed on the Mayall 4-m telescope at Kitt Peak National Observatory in 2018. A new wide-field corrector will provide an 8 square degree field-of-view at prime focus. 5,000 optical fibers will feed 10 triple-arm high-throughput spectrographs, simultaneously covering 360–980 nm and reaching spectral resolution R = 4000 in the infrared. Individual actuators rapidly position the fibers with the help of an integrated feedback mechanism that compares fiber position to the requested target locations allowing a rapid cadence of observations. We present the design of the DESI readout and instrument control system. We will focus on nouvelle design aspects of the system architecture and discuss the fiber positioning software including how we map on sky targets to focal plane coordinates with real time measurements of optical distortions, telescope pointing and environmental parameters.

9913-26, Session 6

Efficient receiver tuning using differential evolution strategies

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Differential evolution (DE) is a powerful and computationally inexpensive optimization strategy that can be used to search an entire parameter space or to converge quickly on a solution. The Kilopixel Array Pathfinder Project (KAPPa) is a heterodyne receiver system delivering 5 GHz of instantaneous bandwidth of the tuning range 645-695 GHz. The fully automated KAPPa receiver test system uses performance feedback and DE to find optimal receiver tuning without any human intervention. We present an adaptation of DE for use in rapid receiver characterization. The KAPPa DE code is written in Python 2.7 and is fully integrated with the KAPPa instrument control code, data processing, and visualization code.

The goal of KAPPa is to develop the technologies needed to realize heterodyne focal plane arrays containing ~1000 pixels. The receiver characterization phase of KAPPa provides many challenges, one of which is investigating large parameter spaces to find optimal receiver tuning, a task that was considerably difficult using via by-hand techniques. For example, a typical parameter space includes Superconducting-Insolating-Superconducting (SIS) junction bias voltage, magnetic field strength across the SIS junction, local oscillator (LO) power, LO frequency, and output frequency (IF) bandwidth. For future, large-scale arrays, it is desirable to do characterization or tuning in an automated fashion without the need for human intervention. Many optimization strategies exist, but DE can be set to converge to a solution rapidly with minimal computational overhead, making it ideal for time and budget constraints.

One of the more subtle aspects of DE is setting the “cost function” which is used to rank sets of input parameters. The cost function can be any linear combination of receiver performance, receiver stability, or any other measureable property. We present our DE strategies and show some simple cost functions that may be useful for other similar applications. Some additions to the DE strategy were required to address receiver instability that may give an anomalously high cost function result.

We discuss how DE is used in the KAPPa system and how well it preforms. Our system is fundamentally limited by the settling time of the electronics in response to input parameter changes and the speed of our optical chopper, thus some parameter spaces are still too large to consider the parameter space robustly searched. Currently, measuring the receiver sensitivity for a single set of parameters takes 4 seconds. We look toward the future of ~1000 pixel array receivers and consider how the KAPPa DE system might be applied. Additionally, we will present future ideas for adapting the current code to rapidly tune telescope receivers and choose the best possible mix of stability and sensitivity for a given run or installation.

9913-27, Session 6

The SAAO instrumentation software architecture and the SHOC instruments

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In addition to the premium Southern African Large Telescope (SALT), the South African Astronomical Observatory (SAAO) operates a number of smaller telescopes. These productive and well-established telescopes are kept scientifically relevant by being updated with a modern suite of instruments. We describe a software architecture suitable for modern instrumentation projects at the SAAO, and present as a case study the Sutherland High-Speed Optical Cameras (SHOC).

Traditionally, instrumentation software at the SAAO was developed by astronomers using the instruments. As such, a range of programming styles and languages was used, user interfaces were not always intuitive, and modern practices such as version control were rare (and often the source code was no longer available). It was frequently hard to meld the output of third-party software with the locally- developed software in such a way that the all parameters relevant to observations were included in the output data. We wanted to develop a standardized way of doing software, incorporating modern design principles, with the aim of easing maintenance, promoting code re-use, and allowing coherent user interfaces and data outputs.

To this end, we have developed a distributed architecture, with individual instrument components represented by free-standing drivers. These may be programmed in whichever language is most suitable; we have largely standardized on C++ and Python. The driver processes are held together and communicate over a network with a central controlling process. The interfaces are defined using Apache Thrift, which provides both data serialization and a way to make remote procedure calls. The controller process is written in Python, and allows a variety of user interfaces to to be developed. These include command line interfaces (used for development, testing and diagnostics), traditional Qt-based graphical user interfaces, and web-based interfaces.

The modularity of the system means that components can be worked on individually, and added to the system as needed. Furthermore a fault in a single component need not bring down the whole system. Components are are inherently network-aware, and as such the new software architecture facilitates our goal of creating instruments which are remotely accessible and which should eventually be robotically operable.

The SHOC systems were designed for high-speed, accurately timed imaging work, primarily on the 74-inch and 40-inch telescopes at the SAAO’s Sutherland observing station. The base SHOC systems comprise a filter wheel, a GPS receiver for timing triggers, an Andor iXon camera, and a control PC. Plug-in modules allow access to telescope pointing coordinates and information about current atmospheric conditions. The controller layer is responsible for coordinating each of these, and arranges for information from each of the subsystems to be stored in the output data.

The SHOC user interface is web-based, and allows remote control and viewing of the instrument components from a PC, tablet or phone. The interface uses JS9 to provide a configurable view of the data as it is captured. JS9 is a JavaScript port of the well-known DS9 software, and so is familiar to many observers.

9913-28, Session 6

World coordinate information for the Daniel K. Inouye Solar Telescope

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It is a top level science requirement that data from the Daniel K Inouye Solar Telescope (DKIST) is archived and made available to the world wide astronomical community. Data from DKIST must contain sufficient meta data to allow proper post processing. In this paper we describe how the Telescope Control System (TCS) and Instrument Control Systems (ICS) work together with the camera systems to provide the information to achieve this goal. In particular we will show how the world coordinate information (WCI) produced by the various subsystems can be used to generate FITS headers for post-processing off summit, how it is used to meet the Observatory Control System (OCS) requirements to map between solar coordinate systems and pixels in an image, how positions on one detector can be mapped onto positions on another and how if multiple instruments are in use then the appropriate WCI is attached.

We will show how the Wavefront Correction Control System (WCCS) context viewer plays a key role in establishing the transformation chain from pixels in an image to sky coordinates as it provides the link between the instrument coordinate frames that are fixed relative to each other in the coude room and the TCS defined x, y coordinate frame.

9913-29, Session 6

The Infrared Imaging Spectrograph (IRIS) for TMT: motion planning with collision avoidance for the on-instrument wavefront sensors

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The InfraRed Imaging Spectrograph (IRIS) will be a first-light client instrument for the Narrow Field Infrared Adaptive Optics System (NFIRAOS) on the Thirty Meter Telescope. IRIS includes three configurable tip/tilt (T/T) or T/T/focus On-Instrument Wavefront Sensors (OIWFS). These sensors are positioned over natural guide star (NGS) asterisms using movable polar-coordinate pick-off arms (POAs) that patrol an approximately 2-arcminute circular field-of-view (FOV). The POAs are capable of colliding with one another, so an algorithm for coordinated motion that avoids contact is required. We have adopted an approach in which arm motion is evaluated as the downhill gradient of a scalar potential field that includes an "attractive" component towards the goal configuration (locations of target stars), and repulsive components to avoid obstacles (proximity to adjacent arms). This technique is computationally inexpensive, and produces smooth and efficient trajectories. Results of full motion simulations, including mitigation of problematic system configurations, with acquisition time statistics, are presented.

9913-30, Session 6

AAO Starbugs: software control and path-finding algorithms

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The AAO's TAIPAN instrument deploys 150 9mm diameter Starbug robots to position optical fibres to accuracies of 0.5 arcsec, on a 30cm glass field plate on the focal plane of the 1.2 m UK-Schmidt telescope. This paper describes the software system developed to control and monitor the Starbugs, with particular emphasis on the automated path-finding algorithms, and the metrology software which keeps track of the position and motion of individual Starbugs as they independently move in a crowded field.

The software employs a tiered approach to find a collision-free path for every Starbug, from its current position to its target location. This consists of three path-finding stages of increasing complexity and computational cost. For each Starbug a path is attempted using a simple method. If unsuccessful, subsequently more complex (and expensive) methods are tried until a valid path is found or the target is flagged as unreachable.

The challenge is to ensure that a given path takes a minimum amount of time to execute, but that doing this does not prevent a neighbouring Starbug from reaching its target. Additionally, the algorithm must ensure that the umbilical which tethers each Starbug to the instrument (and carries the science fibre) is not entangled with that of other Starbugs in their simultaneous movement across the field plate, as this would increase the risk of reconfiguration failure in subsequent exposures.

Simulations show that this multi-stage approach allows the field to be reconfigured within the required 5 minutes for the majority of expected target configurations. We will show the results of initial tests with the instrument using the final production Starbugs.

9913-31, Session 6

Collision-free coordination of fiber positioners in multi-object spectrographs

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Many fiber-feb spectroscopic survey projects, such as DESI, PFS and MOONS, will use thousands of fiber positioners packed at a focal plane. To maximize observation time, the positioners need to move simultaneously and reach their targets swiftly. We have previously presented a motion planning method based on a decentralized navigation function for the collision-free coordination of the fiber positioners in DESI. In MOONS, the end effector of each positioner handling the fiber can reach the centre of its neighbours. There is therefore a risk of collision with up to 18 surrounding positioners in the chosen dense hexagonal configuration. Moreover, the length of the second arm of the positioner is almost twice the length of the first one. As a result, the geometry of the potential collision zone between two positioners is not limited to the extremity of their end effector, but surrounds the second arm.

In this paper, we modify the navigation function to take into account the larger collision zone resulting from the geometrical shape of the positioners. The proposed navigation function takes into account the configuration of the positioners as well as the constraints on the actuators, such as their maximal velocity and their mechanical clearance. Considering the fact that all the positioners' bases are fixed to the focal plane, collisions can occur locally and the risk of collision is limited to the 18 surrounding positioners. The decentralizing motion planning and trajectory generation takes advantage of this limited number of positioners and the locality of collisions, hence significantly reduces the complexity of the algorithm to a linear order. The linear complexity ensures short computation time. In addition, the time needed to move all the positioners to their targets is independent of the number of positioners. These two key advantages of the chosen decentralization approach turn this method to a promising solution for the collision-free motion-planning problem in the next-generation spectroscopic survey projects. A motion planning simulator, exploited as a software prototype, has been developed in Python.
The pre-computed collision-free trajectories of the actuators of all the positioners are fed directly from the simulator to the electronics controlling the motors. A successful demonstration of the effectiveness of these trajectories on the real positioners as well as their simulated counterparts are put side by side in the following online video sequence (https://goo.gl/YuwwsE).

9913-32, Session 7

Exploratory visualization of astronomical data on ultra-high-resolution wall displays *(Invited Paper)*

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Ultra-high-resolution wall-sized displays feature a very high pixel density over a large physical surface. For instance, WILD, the first wall display we set up in our laboratory, has a total resolution of 20480?6400 = 131 megapixels for a surface area of 5.5m?1.8m. Such platforms have properties that make them well-suited to the visualization of very large datasets. They can represent the data with a high level of detail while at the same time retaining context: users can transition from an overview of the data to a detailed view simply by physically moving in front of the wall display. Wall displays also offer good support for collaborative work, enabling multiple users to simultaneously visualize and interact with the displayed data. To make them interactive, wall-sized displays are increasingly coupled with input devices such as touch frames, motion-tracking systems and wireless multitouch devices, in order to enable multi-device and multi-user interaction with the displayed data.

Application areas for such visualization platforms range from the monitoring of complex infrastructures and crisis management situations to tools for the exploratory visualization of scientific data. In this paper, we describe one such application, called FITS-OW, that enables astronomers to visualize and interact with very large FITS images and collections thereof. They can pan and zoom in images that are several hundred thousand pixels in both width and height, overlay the results of data analyses, fetch and display additional images of a specific object or region in the sky, showing observations in different ranges of the electromagnetic spectrum or at different times. Additionally, FITS-OW lets astronomers query databases such as Simbad servers, and visualize the results of such queries in-place, right next to the corresponding source in the image. The very high pixel density of wall displays means that detailed information can be shown for multiple sources simultaneously, including multiple measurements as well as research articles retrieved dynamically through links found in relevant databases.

We explain how we enable astronomers to perform these operations using interaction techniques that were designed specifically for wall displays, using direct manipulation and gestures performed on the wall's surface or on handheld tablets: adjusting the scale and color mapping used to render the raw, high-dynamic-range FITS data; overlaying and manually compositing multiple bands; measuring the brightness, colors and light curves of astronomical sources; making queries and adjusting object filters. We also explain how we addressed related technical challenges. Indeed, ultra-high-resolution wall displays are often driven by clusters of computers (the above-mentioned WILD platform uses 32+1 graphics processing units in 16+1 computers) and involve heterogeneous input devices, which causes problems of data sharing, graphics rendering, and handling multiple user input channels. We describe FITS-OW's architecture and our solution to the specific challenges that this application raised: the generation of FITS tile pyramids and their multi-scale rendering; the computation of sky coordinates; queries to sky catalogs; the dynamic adjustment of scale, color mapping and graphics compositing settings, and the underlying input management framework.

9913-33, Session 7

Prototyping the graphical user interface for the operator of the Cherenkov Telescope Array

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The Cherenkov Telescope Array (CTA) is a planned gamma-ray observatory. CTA will utilize imaging atmospheric Cherenkov telescopes (IACTs), using three different telescope types. The telescopes will be deployed in two sites, Northern and Southern, which will respectively include about 100 and about 20 telescopes. Previous IACT experiments were restricted to up to five telescopes. Consequently, the design of a graphical user interface (GUI) for the operator of a CTA site involves new and interesting challenges. To name a few, the GUI will need to convey information for various levels of complexity; on the level of the entire array (100 telescopes); the level of sub arrays (between 1 and 32 groups); or the level of a single telescope and the associated sub-systems. In addition, multi-telescope views for a given sub-system will also be required, taking into account the differences between the telescope types. The GUI will also need to be highly responsive, and to integrate different interfaces to CTA software (databases, live feeds etc.).

CTA members have started collaboration with experts from INRIA in the field of human-computer interface. Such interaction has proven beneficial for other multi-instrument experiments, such as the Atacama Large Millimeter/submillimeter Array (ALMA). Following a two-day workshop in DESY in May 2015, we have defined an initial set of requirements for the operator GUI, and have begun prototyping activity.

Our current prototype is based on web technology. The back-end is a Python based server called Pyramid. A Python framework has the advantage of being very versatile, incorporating the ability to use many off-the-shelf libraries for computation, communication, multi-threading and multi-processing. The front-end is a web browser; it displays data generated with Javascript, using an open-source library called d3.js. The latter is a data-driven framework, with integrated mechanisms for displaying, updating and animating vector graphics. Communication between the back-end and the front-end of the GUI is performed using web-sockets. These allow asynchronous communication, facilitating quick and responsive GUI behaviour. As part of the prototyping process, we have implemented such features as panel synchronization, and semantic zooming. The latter provides a contextual level of complexity; based on the actions of the user, graphical elements change and reflect different types of information.

9913-34, Session 7

Firefly: embracing future web technologies

William W. Roby, Xiuqin Wu, Loi Ly, Tatiana Goldina, Lijun Zhang, California Institute of Technology (United States)

We are currently in the golden age of JavaScript web technology. We now can build web applications on a scale that would have never been considered a few years ago. With its unprecedented sophistication, web development is constantly changing and improving in speed, capabilities and ease of development.

At IPAC/Caltech, we have developed the Firefly web archive and visualization system used in production for the last eight years in many missions while giving the scientist significant capabilities to study data. Firefly provided the first completely web based FITS viewer as well has having significant data, tabular and plotting visualizers. Further, it will be

used for the science user interface of the LSST telescope which goes online in 2021. Firefly must meet the needs of archive access and visualization for the 2021 LSST telescope, and must serve astronomers beyond the year 2030.

Currently, our team has faced the fact that this software will become obsolete in the next couple of years. This is our challenge with the Firefly visualization library.

In the last year, we have ported the Firefly to cutting edge web technologies. Embarking on this massive overhaul is no small feat to say the least. Choosing the technologies that will maintain a forward trajectory in a future development project is always hard and often overwhelming. When a team must port 200,000 lines of code for a production-level product there is little room to make poor choices. In this approach, we believe our new code will utilize all the current breakthroughs in stability, testability, speed, and reliability while still allowing our teams to work on large applications.

This talk will give an overview of the most modern web technology and lessons learned in our conversion from GWT based system to React/Redux based system.

9913-35, Session 7

Observation management challenges of the Square Kilometre Array

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The Square Kilometre Array (SKA) will be the world's most advanced radio telescope, designed to explore some of the biggest questions in astronomy today, such as the epoch of re-ionization, the nature of gravity and the origins of cosmic magnetism. SKA1, the first phase of SKA construction, is currently being designed by a large team of experts world-wide. SKA1 comprises two telescopes: a 200-element dish interferometer in South Africa and a 130000-element dipole antenna aperture array in Australia.

To enable the ground-breaking science of the SKA an advanced Observation Management system is required to support both the needs of the astronomical community users and the SKA Observatory staff. This system will ensure that the SKA realises its scientific aims and achieves optimal scientific throughput. This paper provides an overview of the design of the system that will accept proposals from SKA users, and result in the execution of the scripts that will obtain science data, taking in the stages of detailed preparation, planning and scheduling of the observations and onwards tracking. It describes the unique challenges of the differing requirements of two telescopes, one of which is very much a "software telescope", including the need to schedule the data processing as well as the acquisition, and to react to both internally and externally discovered transient events. The scheduling of multiple parallel sub-array use is covered, along with the need to handle commensal observing - using the same data stream to satisfy the science goals of more than one project simultaneously. An international team from academia and industry, drawing on expertise and experience from previous telescope projects, the virtual observatory and comparable problems in industry, has been assembled to design the solution to this challenging but exciting problem.

9913-36, Session 8

Status report of the SRT radiotelescope control software: the DISCOS project

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The Sardinia Radio Telescope (SRT) is a 64-meter fully steerable radio telescope. It is provided with active surface to correct for gravitational deformations, allowing observations from 300 MHz to 100 GHz. At present, three receivers are available: a coaxial LP-band receiver (305-410 MHz and 1.5-1.8 GHz), a C-band receiver (5.7-7.7 GHz) and a 7-feed K-band receiver (18-26.5 GHz). Several back-ends are also available in order to perform the different data acquisition and analysis procedures requested by the various scientific projects.

The design and development of the SRT control software started in 2004, and now belongs to a wider project called DISCOS (Development of the Italian Single-dish Control System), which provides a common infrastructure to the three Italian radio telescopes (Medicina, Noto and SRT dishes). DISCOS is based on the Alma Common Software (ACS) framework, and currently consists of more than 500K lines of code. It is organized in a common core and three specific product lines, one for each telescope. Recent developments, carried out after the conclusion of the technical commissioning of the instrument (December 2013), consisted in the addition of several new features in many parts of the observing pipeline, spanning from the motion control to the digital backends for data acquisition and data formatting; we will briefly describe such improvements.

More importantly, in the last two years we have assisted the astronomical validation of the SRT radiotelescope, leading to the opening of the first public call for proposal in late 2015. During this period, while assisting both the engineering and the scientific staff, we massively employed the control software testing all of its features: in this process we received our first feedback from the users and we could see how the system performed in a real-life scenario, drawing the first conclusions about the overall system stability and performance. We will take into exam how the system behaves in terms of network load and system load, how it reacts to failures and errors, and what components and services seem to be the most critical parts of our architecture, showing how the ACS framework has an impact on those aspects.

Moreover, the exposure to public utilization has highlighted the major flaws in our development and software management process, which had to be tuned and improved in order to achieve faster release cycles in response to user feedback and safer deploy operations. In this regard we will show how the introduction of testing practices, along with continuous integration, helped us to meet higher quality standards.

Having identified the most critical aspects of our software, we will conclude showing our intentions for the future development of DISCOS, both in terms of software features and software infrastructures.

9913-37, Session 8

Status report of the end-to-end ASKAP software system: towards early science operations

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The Australian SKA Pathfinder (ASKAP) is a novel centimetre radio synthesis telescope currently in the commissioning phases and located in the midwest region of Western Australia. It comprises of 36 x 12 m diameter reflector antennas each equipped with state-of-the-art and award winning Phase Array Feeds (PAF) technology. The PAFs provide a wide, 30 square degree field-of-view by forming up to 36 separate dual-polarisation beams at once. This results in a high data rate: 70 TB of correlated visibilities in an 8 hour observation, requiring custom-written, high-performance software running in dedicated High Performance Computing (HPC) facilities. The first 6 antennas equipped with first-generation PAF technology (Mark I), named the Boolardy Engineering Test Array (BETA) has been in used since 2014 as a platform to test PAF calibration and imaging techniques, and along the way it has been producing some great science results. Commissioning of the ASKAP Array Release 1, that is the first 6 antennas with second-generation PAFs (Mark II) is currently under way.

An integral part of the instrument is the Central Processor platform hosted at the Pawsey Supercomputing Centre in Perth, which executes the custom-written software pipelines, designed specifically to meet the ASKAP imaging requirements of wide field of view and high dynamic range. There are three key hardware components of the Central Processor: The ingest nodes (16 x node cluster), the fast temporary storage (1 PB Lustre filesystem) and the processing supercomputer (200 TFlop system). This High-Performance Computing (HPC) platform is managed and supported by the Pawsey support team. Due to the limited amount of data generated by BETA and the first ASKAP Array Release, the Central Processor platform has been running in a more “traditional” or user-interactive mode. But this is about to change: integration and verification of the online ingest pipeline starts in early 2016, which is required to support the full 300 MHz bandwidth for Array Release 1; followed by the deployment of the real-time data processing components. In addition to the Central Processor, the first production release of the CSIRO ASKAP Science Data Archive (CASDA) has also been deployed in one of the Pawsey Supercomputing centre facilities and it is integrated to the end-to-end ASKAP data flow system.

This paper describes the current status of the “end-to-end” data flow software system from preparing observations to data acquisition, processing and archiving; and the challenges of integrating an HPC facility as a key part of the instrument. This paper also shares some lessons learned since the start of integration activities and the challenges ahead in preparation for the start of the Early Science program.

9913-38, Session 8

MAISIE: a multi-purpose astronomical instrument simulator environment

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Astronomical instruments often need simulators to preview their data products and test their data reduction pipelines. Instrument simulators tend to be purpose-built with a single instrument in mind, and attempting to reuse one of these simulators for a different purpose is often a slow and difficult task. MAISIE is a simulator framework designed for reuse on different instruments. An object-oriented design encourages reuse of functionality and structure, while offering the flexibility to create new classes with new functionality. MAISIE can just as easily build simulators for single or multi-channel instruments and ground or space based instruments. To remain easy to use and to facility the sharing of simulators across teams, MAISIE is written in Python, a freely available and open-source language. New functionality can be created for MAISIE, on a general or specific basis, by creating new classes that represent optical mediums. This approach allows new and novel instrument to add functionality and take advantage of the existing MAISIE classes. MAISIE has recently been used successfully to develop the simulator for the JWST/MIRI- Medium Resolution Spectrometer.

9913-39, Session 8

ALMA common software from development to operations

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ALMA, an international partnership of Europe, North America and East Asia in cooperation with the Republic of Chile, is one of the largest astronomical observatories in existence. It operates a single telescope composed of 66 antennas located on the Chajnantor plateau in Chile. All antennas are now at the ALMA site and the observatory is transitioning towards full-scale science operations.

The ALMA Common Software (ACS), developed by ESO in collaboration with its partners, provides the infrastructure of the distributed software system of ALMA and other projects, being available under the open source LGPL licence.

ACS, built on top of CORBA and DDS middleware, is based on a Component-Container paradigm and provides an API that hides the complexity of the middleware allowing the developer to focus on domain specific issues.

ACS adopts a different interoperable implementation for each of the three supported languages, C++, Java and Python and provides services for distributed programming like transparent remote object invocation and activation, component lifecycle management, publisher/subscriber, distributed error logging, alarm management, configuration database, simulation, deployment, testing and debugging tools.

The transition of the ALMA observatory from construction to operations brings with it that ACS efforts focuses primarily on scalability, stability and robustness to address operational issues rather than on the delivery of new features (although few are still introduced to satisfy operational requirements). The transition came together with a new, shorter, release cycle and a more extensive on-site testing.

For scalability, the most problematic area has been the CORBA notification service, used to implement the publisher subscriber pattern. Problems in that area are intrinsically difficult to debug, because of the asynchronous nature of the paradigm. Therefore, a lot of effort has been spent to improve notification service stability and recovery from run time errors, without having to restart the whole software system.

An investigation of the replacement of CORBA notification channels with DDS has been conducted times ago and looked promising, but further development has been put on hold until the ALMA software will be considered stable enough. A comparison of DDS with a messaging library like ZeroMQ is also foreseen.

The original bulk data mechanism, implemented using the CORBA Audio/Video Streaming Service, showed its limitations and has been replaced with a more performant and scalable DDS implementation.

Operational needs showed soon the difference between releases cycles for Online software (i.e. used during observations) and Offline software, which requires much more frequent releases. As a consequence, offline subsystems started to reduce their dependency on ACS that could not ship libraries and tools common to all the subsystems without substantially impacting their release cycles. The updating of some of the strategic tools like Java must now be done more frequently, e.g. to promptly respond to security issues of web applications.

This paper aims to describe the impact the transition from construction to operations had on ACS, the solution adopted so far and a look into future evolution.

9913-40, Session 8

The ESO astronomical site monitor upgrade

Gianluca Chiozzi, Heiko Sommer, Marc S. Sarazin, Thomas Bierwirth, Dario Dorigo, Ignacio Vera Sequeiros, European Southern Observatory (Germany); Julio Navarrete, Diego del Valle, European Southern Observatory (Chile)

Monitoring and prediction of astronomical observing conditions are essential for planning and optimizing observations at all modern observatories. For this purpose, ESO, in the 90's, developed the concept of an Astronomical Site Monitor (ASM), as a facility fully integrated in the operations of the VLT observatory.

Two essentially identical systems were installed both at Paranal and La Silla, providing comprehensive local weather information (wind, humidity, temperature and dust at different locations) and a Differential Image Motion Monitor (DIMM) for seeing measurement.

By now we had three very good reasons for a major upgrade of these systems:

• The need of introducing new sensors and features to satisfy the requirements of observations using Adaptive Optics.

• Managing hardware and software obsolescence.

• Making the system more maintainable and expandable by integrating off-the-shelf hardware solutions and up to date software technologies.

The new ASM integrates:

• a new DIMM paired with a Multi Aperture Scintillation Sensor (MASS) to measure the vertical distribution of turbulence in the high atmosphere by analysing the scintillation of bright stars.

• a new SLOpe Detection And Ranging (SLODAR) telescope, for measuring the altitude and velocity of turbulent layers in the low atmosphere by means of a triangulation method, in which the turbulence profile is recovered from observations of bright binary stars using a Shack-Hartmann wavefront sensor.

• a water vapour radiometer to monitor with high precision and time resolution water vapour content of the atmosphere, allowing to execute observations in the infrared in periods of low precipitable water vapour.

• the old weather tower, that is being refurbished with new sensors.

The telescopes used and the devices integrated are commercial products and we have used as much as possible the control system provided by the vendors, limiting our work to the high level coordination and integration and reducing considerably the amount of software developed with respect to the older system.

Still, the existing external interfaces and the overall system architecture, based on the VLT standards, have been maintained for full backward compatibility.

All data produced by the system are now directly fed in real time into a relational database in Paranal which is replicated to Garching. This allows accessing the data easily both for operations and data analysis, in the same way, using traditional RDBMS tools.

A completely new web-based display replaces the obsolete plots with a flexible and highly configurable application that is also made available to external users.

While access to the live data of old system had to be limited to few consoles in the control room because of computing resources and even though the new system makes available much more information, we can now provide a very scalable access both within and outside the observatory.

In this paper we will analyse the architectural and technological choices for the upgrade and discusses the motivations and trade-offs.

9913-41, Session 9

ASTRI SST-2M prototype and mini-array data reconstruction and scientific analysis software in the framework of the Cherenkov Telescope Array

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In the framework of the international Cherenkov Telescope Array (CTA) gamma-ray observatory, the Italian National Institute for Astrophysics (INAF) is developing a dual-mirror, small-sized, end-to-end prototype (ASTRI SST-2M), inaugurated on September 2014 at Mt. Etna (Italy), and a mini-array composed of nine ASTRI SST-2M telescopes, proposed to be installed at the southern CTA site. The ASTRI mini-array is a collaborative effort led by INAF in synergy with the University of Sao Paulo and FAPESP (Brazil) and the North-West University (South-Africa). The project is also including the full data handling chain from raw data up to final scientific products. To this end, a dedicated software for the on-line/on-site/off-site data reduction and scientific analysis is under development for both the ASTRI SST-2M prototype and mini-array. The software is conceived following a modular approach in which each single component and the entire pipeline are developed in compliance with the CTA requirements. Data reduction components are coded in C++/Python/CUDA and wrapped by efficient pipelines written in Python in order to better exploit the parallel computing architectures (multi-core CPUs) and new hardware architectures based on low-power consumption processors (e.g. ARM) and graphic accelerators (e.g. GPUs). The final scientific products are then achieved by either using standard tools (ctools) adopted by the CTA Consortium or using specifically developed Science Tools if needed. In this contribution, we present the framework and the main software components of the ASTRI SST-2M prototype and mini-array data reduction and scientific analysis package, and report the status of its development.

9913-42, Session 9

Implementing a real-time data stream for time-series stellar photometry

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At present, a number of small and medium-sized robotic telescope facilities are equipped to automatically acquire data of transient sources based on alerts received over the Internet. In most cases the data reduction is automated as well and thus results should be available very quickly. However, the publishing of the latest measurements to the wider astronomical community commonly still involves a step requiring human intervention (for example, writing a descriptive Astronomical telegram). As a consequence, even when there is a desire to publish simple magnitude measurements as fast as possible (in case of a currently unfolding transient event of wider interest) there is typically a time lag of a day or more before the community learns if anyone was observing the event at a given time and what measurements were they able (or interested) to perform. This creates a particular problem for the efficient use of a small observatory: should an alert received today about a transient event be included in the observation schedule, or is this event already being (or been) observed by

a larger telescope and the results of the follow-up are just not sent by a telegram yet?

As a first step to remedy this situation, we present a new automated photometric pipeline optimized for time-series photometry that includes a real-time data streaming service. An observer using this resource can automatically reduce images frame by frame as they are being obtained and stream photometric data of selected sources over the Internet. Other observers can then monitor the data stream in real time and make an informed decision whether to perform complementary observations of a transient event in progress. Our current implementation relies on ZeroMQ, a high-performance asynchronous messaging library. The photometric pipeline itself is controlled through the widely used SAOImage DS9 package, so that the interface is user friendly and already familiar to the astronomical community. Incoming images from a telescope are processed in sequence immediately after readout and download, including standard data reduction (bias, dark, flat-fielding, pixel-masking), frame to frame registration in pixel-space and time stamping. Accurate photometric measurements are carried out using both standard aperture as well as optimal photometry algorithms for maximum S/N extraction. For every observed frame, the photometric measurements for a pre-set list of objects are automatically streamed through a TCP/IP port in real-time and the end client can view them either as simple text or an auto-updating plot. Our pipeline is currently being tested with observations made by the 60cm telescope at Astronomical Station Vidojevica in Serbia. The pipeline uses a modular design so that it can be easily implemented or customized as a real-time robotic telescope pipeline on any observatory.

9913-43, Session 9

Automated spectral reduction pipelines

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We present results from the development and operation of the automated data reduction pipeline being used for a diverse range of spectrographs on the Liverpool Telescope. The pipelines perform both the removal of instrumental signatures (bias, dark, flat, distortion etc) and provide science-ready, wavelength calibrated data products to the astronomers promptly after observation. Efficient execution of the observatory's highly automated operations model requires substantial commonality between the software for all the instruments and the spectrographs use a common code base. The unique science drivers of each instrument led to novel hardware solutions which required detailed reassessment of some of the conventional CCD reduction recipes rather than using the widely available software packages. For example, we describe the derivation and application of bias and dark corrections on detectors with neither overscan or shutter. In the context of spectroscopy we compare the quality of flat fielding resulting from different algorithmic combinations of dispersed and non-dispersed sky and lamp flats in the case of spectra suffering from 2d spatial distortions. The LT, a robotic, fully-automated, common-user observatory owned and operated on La Palma by Liverpool John Moores University has a broad optical instrument suite including three spectrographs; the original, facility spectrograph, FRODOSpec and two more specialised instruments developed to address particular science needs. SPRAT offers very high throughput at low dispersion for use in rapidly typing transient sources and LOTUS is heavily optimised for the near ultra-violet (3300-4000A).

9913-44, Session 9

StarDock: shipping customized computing environments to the data

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The ever-increasing size of astronomical data volumes is making the transfer, storage, and processing of data a significant burden for the traditional astronomer. Institutional repositories and pipelines, such as the One Degree Imager - Portal, Pipeline, and Archive (ODI-PPA) have attempted to address some of these concerns by allowing users to remotely configure and run a limited set of software, i.e. for ODI-PPA users, the QuickReduce (QR) pipeline and SWarp stacking application have been made available. While this arrangement is satisfactory for most users, there exists a significant fraction whose work could greatly benefit by being able to run their own customized reduction and analysis software directly on the bulk raw or unstacked images. Satisfying the disparate desires of all potential users into a single pipeline is unfeasible, as is integrating their customized software onto our systems and crafting a usable interface. For a solution, we turn towards Docker, a virtual container system that abstracts the application layer and allows software to run in diverse environments. Our system, under the working title StarDock, begins with a suite of micro-service containers of commonly-used astronomical software tools, including astropy, IRAF, QR, SWarp, Montage, and others. Through our Portal interface, a user creates a template image, defining which of the pre-configured micro-services they'll depend on, downloads the template to their local system along with a sample dataset, and adds their own routines and software. When they are satisfied with their customized container, they upload it back to our system, and request processing time, which can be automated or interactive depending on how they have configured their container. The user also specifies a dataset upon which to operate. Leveraging the existing infrastructure of ODI-PPA and Indiana University, the desired dataset is staged, the container is loaded, and the user can exert exact control of the processing and analysis of their data, and retrieve the results when completed. In this presentation we will discuss the mechanics of StarDock, delve into the construction of the templates, address security concerns, and go through a typical workflow. Although StarDock represents a great shift in how astronomical data analysis has traditionally been done, it is a necessary one to keep astronomers from drowning in the data volumes of tomorrow.

9913-21, Session PS1

Is the workflow model a suitable candidate for an observatory supervisory control infrastructure?

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The LSST requires a hierarchical control of principal sub-systems to co-ordinate the scientific survey and support (early) commissioning. Such software must be implemented in either Java, C++ or Python under Linux. We also require a web-based interface to this system and the ability to run scripts at different sites (main telescope and auxiliary telescope) either independently or in a co-ordinated fashion. We have identified two open source candidates that provide workflow development systems and run-time engines. One (Bonita BPM) is based upon an OMG standard called BPMN 2.0 and the other (Taverna) was supported by European Union funds but has since move to Apache Incubator Project status. In this paper, we report on the current state of these evaluations for observatory supervisory control.

9913-71, Session PS1

WAS: the archive for the WEAVE spectrograph

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The WEAVE spectrograph will be mounted at the WHT 4m telescope and will provide millions of spectra in a 5 years program, starting after its foreseen first light, late 2017. The targets will be stars and galaxies, providing follow up for the GAIA catalogue and a valuable database for the extragalactic community for nearby clusters of galaxies.

The access and retrieval of the information will be through its dedicated archive, the WEAVE Archive System (WAS). This will be developed and maintained at the TNG premised in the same island of the WHT. Its structure foresees the main axis of scalability, virtualization, and high availability.

The NoSQL Cassandra by Apache has been identified as capable to deal with big data and its Solr indexing package as being able to quickly answer to selection criteria needed to exploit the large set of data. The possibility to further expand the variety of tools via its analytics Spark package may reveal the way to proceed for future pipelines on big dataset.

The scalability of this architecture will allow us to expand the hardware as the observations increase the volume needed on disks as well as load on the servers, in a way which would not be possible using more traditional databases. The same, distributed network of resources will allow a very high availability of the system even in case of a point failure. Virtualization could cut overall costs but possibly at expenses of performance.

We present here the first performances on a simulated data set of 20M spectra, using different architectures and hardware choices. The results will be a benchmark for the final, real solution for the WAS archive, which will be built in the next two years.

9913-76, Session PS1

The very high energy source catalogue at the ASI science data center

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The increasing number of Very High Energy (VHE) sources discovered by the current generation of Cherenkov telescopes made particularly relevant the creation of a dedicated source catalogs as well as the cross-correlation of VHE and lower energy bands data in a multi-wavelength framework. The “TeGeV Catalogue” hosted at the ASI Science Data Center (ASDC) is a catalogue of VHE sources observed by ground-based Cherenkov telescopes. The TeGeVcat collects all the relevant information publicly available about the observed GeV/TeV sources. The catalogue contains also information about public light curves while the available spectral data are included in the ASDC SED Builder tool directly accessible from the TeGeV catalogue web page. In this contribution we will report comprehensive description of the catalogue and the related tools.

9913-79, Session PS1

Telemetry correlation and visualization at the Large Binocular Telescope Observatory

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Highly efficient observatory operations rely upon quality metrics evaluation. High quality metrics requires robust and complete observatory telemetry. At the LBTO, a wide variety of telemetry-capturing mechanisms exist. In an effort to make this telemetry data available to a wide audience, we are developing a suite of tools based on in-house and COTS applications. This paper will explore our strategies for consolidating, parameterizing, and correlating this data to achieve easily available, web-based 2D and 3D time series data visualization. This paper discuses the initial set of tools, details for correlation implementation and future considerations for more advanced correlation techniques.

9913-83, Session PS1

The ALMA high-speed optical communication link is here: an essential component for reliable present and future operations

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Announced in 2012, started in 2013 and completed in 2015, the ALMA high-bandwidth communication system has become a key factor to achieve the operational and scientific goals of ALMA. This paper summarizes the technical, organizational, and operational goals of the ALMA Optical Link Project, focused in the creation and operation of an effective and sustainable communication infrastructure to connect the ALMA Operations Support Facility and Array Operations Site, both located in the Atacama Desert in the Northern region of Chile, with the point of presence of REUNA in Antofagasta, about 400km away, and from there to the Santiago Central Office in the Chilean capital through the optical infrastructure created by the EC-funded EVALSO project and now an integral part of the REUNA backbone. This new infrastructure. This new infrastructure completed in 2014 and now operated on behalf of ALMA by REUNA, the Chilean National Research and Education Network, uses state of the art technologies, like dark fiber from newly built cables and DWDM tra nsmission, allowing extending the reach of high capacity communication to the remote region where the Observatory is located. The paper also reports on the results obtained during the first year and a half testing and operation period, where different operational set ups have been experienced for data transfer, remote collaboration, etc. Finally, the authors will present a forward look of the impact of it to both the future scientific development of the Chajnantor Plateau, where many installations area are (and will be) located, as well as the potential Chilean scientific backbone long term development.

This paper could also be in AS-103 - Observatory infrastructure.

9913-87, Session PS1

The online analysis tool of the AGILE gamma-ray mission based on the Level 3 data archive hosted at the AGILE data center

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The AGILE gamma-ray space mission is dedicated to the observation of astrophysical sources of photons with energy E > 100 MeV. The satellite has been launched in April 2007 and it has just completed its ninth year of operations.

The scientific analysis of the AGILE Gamma Ray Imaging Detector (GRID) data, using the official software tools, is based on the creation of scientific maps (sky, exposure and diffuse model maps) and then on the application of Maximum Likelihood algorithms for the detection of sources and extraction of scientific products (source fluxes, spectra, light curves, ...). A scientific analysis that covers all or part of the public AGILE data archive (till 30 June 2015) might need a very long time. In order to speed up this process, a high-level archive of exposure and counts maps in FITS format on 1-day integrations was created. These 1-day integration maps are summed together to cover pre-selected time intervals (2-, 7- and 28-days), and archived together with the corresponding diffuse gamma-ray background maps.

This archive, called the AGILE Level 3 (LV3) archive, can be used as seed for the GRID scientific data analyses of point sources. An interactive AGILE analysis web tool (AGILE-LV3 tool) has been developed at the AGILE Data Center (within the ASDC) to perform these scientific analyses on time scales that may vary from days to months or even longer total time intervals.

In what follows, we will present the web tool interface and the scientific capabilities achieved using the LV3 GRID Archive. The tool allows extracting almost in real time flux and light curve of a source of interest on a specific time interval without the need to locally install any dedicated software. Preliminary results on the study of transient gamma-ray sources over 7- and 28-days timescale using this tool and the AGILE LV3 archive will be also presented.

9913-91, Session PS1

Construction is over! Where do we go from here to further develop the ALMA software?

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The ALMA software was developed over the course of more than 15 years by a worldwide computing team led by ESO, NAOJ and NRAO. At the end of the construction phase in 2012 this team moved seamlessly into the Integrated Computing Team (ICT), with the inclusion of software integration, support and operations groups at the Joint ALMA Observatory (JAO) in Chile. Three years after starting the early ALMA operational phases the ICT is still busy developing improvements to the delivered system and gradually changing focus from new features to stability, robustness, and operational efficiency aspects. As the observatory continues to steadily move forward to reach full operations a plan for the following five years of operations, namely the period 2017-2021, started to be developed jointly by the science, engineering and computing teams in ALMA. The purpose of this paper is to report the key initiatives currently been brought forward by the ICT for the five years look ahead plan and to explain how they will contribute to ALMA strategic goals in the years to come.

9913-95, Session PS1

Operational logs analysis at ALMA observatory based on ELK stack

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During the operation in the ALMA observatory, a huge amount of logs files are generated in daily basis. As the ALMA software is still under continuous evolution, logs are not only useful to diagnose failures detected during operation, but are also needed to depict long term performance analysis and provides a quick. Historically, log files are kept in XML format and saved into a file repository. Developers and front line support engineers are the most common users of this files in daily basis. Depending on the problem to diagnose, specific groups of files are downloaded and inspected with editors at users preference, which doesn't allow to filter or search efficiently. We decided to improve the usability, and in addition, to exploit the valuable information available in logs files.

The size of our current log database is measured in Terabytes, so an infrastructure to handle big data is required in order to answer the different questions. In this work we describe the implemented solution to face this problem, its applications and the intermediate steps that led to the final architecture. After initial evaluation with different alternatives, we chose ElasticSearch (ES) as the backend database, coupled with Logstash as pipeline and Kibana as a graphical front end. This set of tools is known in the literature as ELK stack and is the de facto open source standard for storing logs and further data analysis. ES features horizontal growth capability and high speed responses upon queries. In the other hand, Kibana provides a very good framework which allow us to quickly create graphs and group them into dashboards focused on specific topics.

To interface with ALMA software, once logs files are generated and moved into an external storage, a process reads XML logs and insert them into the this platform. This approach provides a fully decoupled mechanism and has zero impact in the operation. During normal operation, the software generates an average of 10.000 logs per second, and 3 Terabytes of disks space are required in order to keep 6 months of logs online. During the last year, Software Operation Support group (SOFTOPS) has created several dashboards that display fresh information regarding to the observation behavior of previous night. For example, to track new occurrences of well known issues which avoids repeat the investigation, another example is an estimation of system usage, system restarts, antenna hardware failures, etc. All these dashboards are displayed in a set of screens located in the front of SOFTOPS offices and during each morning, they provide an early overview of the amount of works that need to be addresses by the rest of the day. Finally, we propose further actions that can be done with this infrastructure, i.e: performance trending analysis, software release characterizations, errors prediction, among others.

9913-99, Session PS1

The open microscopy environment: open image informatics for the biological sciences

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Despite significant advances in biological imaging and analysis, major informatics challenges remain unsolved: file formats are proprietary, storage and analysis facilities are lacking, as are standards for sharing image data and results. While the open FITS file format is ubiquitous in astronomy, astronomical imaging shares many challenges with biological imaging, including the need to share large image sets using secure, cross-platform APIs, and the need for scalable applications for processing and visualisation.

The Open Microscopy Environment (OME) is an open-source software framework developed to address these challenges. OME tools include - an open data model for multi-dimensional imaging (OME Data Model); an open file format (OME-TIFF) and library (Bio-Formats) enabling free access to images (5D+) written in more than 145 formats from many imaging domains including FITS; and a data management server (OMERO).

The Java-based OMERO client-server platform comprises an image metadata store, an image repository, visualization and analysis by remote access, allowing sharing and publishing of image data. OMERO provides a means to manage the data through a multi-platform API. OMERO's model-based architecture has enabled its extension into a range of imaging domains, including light and electron microscopy, high content screening, digital pathology and recently into applications using non-image data from clinical and genomic studies. This is made possible using the Bio-Formats library.

The current stable release, OMERO 5.2, includes a single mechanism for accessing image data of all types -- regardless of original file format -- via Java, C/C++ and Python and a variety of applications and environments (e.g. ImageJ, Matlab and R). OMERO includes SSL-based secure access, distributed compute facility, filesystem access for OMERO clients, and a scripting facility for image processing. An open script repository allows users to share scripts with one another. A permissions system controls access to data within OMERO and enables sharing of data with users in a specific group or even publishing of image data to the worldwide community through a web client. This web client provides a framework the creation of custom applications.

Importing these large datasets is fast, and data are stored and used in their original file format, without duplication, and can be accessed by 3rd party software. Several applications using OMERO have now been released by the OME Consortium, including Matlab-based fluorescence lifetime exponential fitting and object tracking modules, two image-based search applications, and an automatic image tagging application.

OMERO and Bio-Formats run the JCB DataViewer, the world's first on-line scientific image publishing system and several other institutional image data repositories.

9913-103, Session PS1

An overview of space weather data system

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Space Weather Data System (SWDS) has become a main factor for space weather research and data service in Korea Astronomy and Space Science Institute (KASI). This paper describes the hardware system, pipeline, data archive, process and visualization software, and web service of SWDS. The goal of SWDS is fast, stable and effective data publish. The hardware system consists of several servers and storage which are separated by function or data type. Between servers and storage communicate through the 10Gbps network switch. SWDS doesn't have database management system but instead, we use file system of directory structure. We have implemented specific application software for various data source, data format and communication protocol, and developed web services to distribute space weather data.

9913-107, Session PS1

Advanced GLS map-making for the Herschel's photometers

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INTRODUCTION: The Herschel space telescope hosted two infrared photometers, namely the Photodetector Array Camera and Spectrometer (PACS) and the Spectral and Photometric Imaging Receiver (SPIRE). The production of sky images from the photometers' output, a process called data reduction or map-making, is critical for the full exploitation of the instruments and is a difficult task, due to the many disturbances affecting the data. Generalised Least Squares (GLS) estimation is an important map-making technique, exploited by several reduction software. However, implementation of GLS for Herschel data is far from trivial and requires specific pre- and post-processing, as better illustrated in [1]. In this paper, we present three improvements of the GLS processing pipeline, aimed at increasing the estimation quality.

INITIAL GUESS: The GLS image estimate has a closed form expression which, however, involves the inversion of large matrices and cannot be evaluated directly. As a result, the image is obtained by means of an approximate, iterative algorithm, which requires an initial guess to start with. In theory, the iterative procedure will converge irrespectively of the initial guess. However, in practice, the convergence may be difficult or impossible to achieve if the guess is not properly selected. In the paper, we

discuss three ways of selecting the initial guess and their relative merits.

DATA SYNCHRONISATION: The sensors of PACS and SPIRE are bolometers placed on the focal plane. During an observation, the telescope pointing is moved along a given scan trajectory, covering the sky area under observation, and the output of each bolometer is sampled at regular times, producing a sequence of readouts that is termed a timeline. Among other problems, the timelines may be affected by a time-shift, due to delays in the processing or to a systematic error in the timing system. This time-shift translates into a systematic pointing error, which shifts all the readouts along the scan trajectory. The shift has a detrimental impact on the image quality, which may be severe for some observation modes. In the paper, we tackle this problem and, in particular, we first extend the data model of [1] in order to account for the shift and next develop an Iterative Synchronisation Algorithm (ISA) for estimating and compensating the shift.

PIXEL NOISE: The estimated image is constituted by a regular array of pixels. However, the readouts' sampling points are not disposed on a regular grid. In other words, the sampling point is not in the pixel center but is randomly placed inside the pixel. This fact is usually neglected by GLS map-makers, which typically employ a nearest neighbour rule, assigning all the readouts to the pixel center. As we show in the paper, this effect can be modelled as an additional noise affecting the readouts, called the pixel noise. This noise may severely reduce the image quality and may introduce a strong distortion in the estimate. In the paper, we tackle this problem and, in particular, we first extend the data model of [1] in order to account for the pixel noise and next discuss how the GLS estimation has to be modified accordingly.

RESULTS: We discuss the image quality improvement that can be achieved using the techniques introduced in the paper by presenting a rich set of examples and experiments, using both real and simulated data.

[1] L. Piazzo et al.: "Unimap: a Generalised Least Squares Map Maker for Herschel Data", {em MNRAS.}, Vol. 447, pp. 1471-1483, 2015.

9913-110, Session PS1

Data reduction software for the Mid-Infrared E-ELT Imager and Spectrograph (METIS) for the European Extremely Large Telescope (E-ELT)

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In this paper we present the current status of the design of the science data reduction pipeline and the corresponding data flow system for METIS.

It will be one of the first three instruments for the E-ELT and feature diffraction limited imaging, low/mid resolution spectroscopy and high resolution integral field spectroscopy (IFS) at mid-infrared wavelengths between 3 - 19 μm (L/M/N/Q1 bands). METIS will employ a variety of observing modes that consist of L/M band imaging and spectroscopy, N/Q1 band imaging and spectroscopy and L/M/N band integral field spectroscopy. METIS will be able to work in parallel mode, which means that it can observe simultaneously with the L/M detector and N/Q1 detector.

Due to the thermal radiation from the telescope, detector and the Earth's atmosphere, the detection noise is orders of magnitude higher than the flux received from the science target. Instrument elements (mirrors, detectors, mechanics, support structures, etc.) will thus be encapsulated and cooled below 40 Kelvin in order to eliminate as many sources of unwanted thermal radiation as possible. The warm elements of the telescope and the sky itself still contribute massive amounts of flux compared to the radiation of the science target. Therefore, the detectors will have to be read out on sub-second time scales. The maximum amount of data produced is roughly 6 terabyte per 10 hours of observation in burst mode of the L/M detector with a read out rate of 20 frames per second.

A reliable and robust data flow system is necessary in order to properly handle the acquired data. We will deliver software that conforms to ESO's (European Southern Observatory) standards and processes data in a cascade of three levels. First, the observatory pipeline provides event driven and on the fly data processing. Second, the quality control (QC) pipeline processes data of a complete observing night and delivers QC parameters, generates master calibration frames and quantifies data to check for instrument health. Third, the science grade pipeline & desktop environment enables processing of the data with the best calibration frames achievable and provides modular software recipes. Finally, a set of workflows for ESO REFLEX will provide clear and neatly arranged science grade data reduction cascades for METIS.

This software will make heavy use of the common pipeline library (CPL) and the upcoming high level data reduction library (HDRL) provided by ESO.

9913-116, Session PS1

A distributed infrastructure for publishing VO services: an implementation

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A complete astrophysical publishing environment, working as a helper system for an astrophysical data center, requires various components, from custom data back ends up to standardized front end solutions. VO technologies, standards and implementations, promoted by the International Virtual Observatory Alliance (IVOA), are a suitable solution for front end interfaces devoted to data discovery and access. A publishing system to generate VO services out of configuration steps can be a useful help to data providers and, for this reason, the Italian center for Astronomical Archives data center developed a first prototype to perform this task. However, being the software monolithic and difficult to maintain due to standard's changes and scalability requirements, a new solution was needed. This contribution describes both the design and the implementation details of the latter, enlightening its maintainable, distributed, modular and scalable architecture. Indeed, the new publisher is multithreaded and multiprocess to be scalable both vertically and horizontally. Multiple instances of the modules can run on different machines to ensure high performance and high availability, and this will be true both for the interface modules of the services and the back end data access ones. The system uses message passing to let its components communicate through an AMQP message broker that can itself be distributed to provide better scalability and availability. An initial implementation of the system has been realized by a couple of IVOA Simple Cone Search protocol based services. The first one uses a servlet as the interface module and a JDBC based MySQL database as the back end one, thus relying completely and coherently on Java technology. The second one, even if it is using a similar servlet interface, passes its incoming requests through the broker to a Python coded back end module, accessing a JSON formatted catalogue. Both the services were made to work together in two different scenarios: a simple cloud environment and a single machine. In particular, the second deployment was carried out with the aim of comparing performances with the previous publishing solution, which will be discontinued. It is worth to notice that, even if this environment is not optimal (since it does not fully exploit the scalability features of our new proposal), the performance comparison with respect to the previous publisher resulted very encouraging to further pursue the development of this new publishing framework.

9913-122, Session PS1

DockQR: a dockerized quick reduce astronomical pipeline

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The QuickReduce pipeline has been an invaluable part of the One Degree Imager - Portal, Pipeline, and Archive (ODI-PPA) system, with its role in producing both operator produced standard calibrated data products and user customized calibrated images, and in enabling the execution of the SWarp stacking application within PPA. QuickReduce is also available for ODI users and others to download and deploy on their own compute resources but this requires a certain level of expertise with the Linux Operating System, including deployment of specific packages like Python and Python modules (numpy/scipy, etc.), the installation of additional software libraries (e.g. the GNU Scientific Library) as well as observatory-supplied calibration data; some of these steps also require administrative privileges. Some astronomers have successfully executed QuickReduce on their own resources but we wanted to to expand the breadth of users who are able to do this. We considered potential solutions, for example: bundling software into RPMs or the like but executing the pipeline in a virtual container environment quickly bubbled up to the top as the simplest and most practical solution. We picked the widely used Docker as our container application, and built a readily available Docker container, DockQR, that includes not only the QuickReduce pipeline source code but also all of its dependences with various possible execution schemes as outlined below. The key advantage to this approach over the bundled software approach is that it is platform independent, and does not require different sets of bundles (for example: RPMs for Red Hat Linux distros, DMG on Mac); Users of any modern Docker-enabled Operating System (Linux distributions like RHEL7, CentOS7, Debian, Ubuntu, SLES; Mac OS) can get a ready-to-execute pipeline without being expert Linux system administrators and without superuser privileges. Users can also execute DockQR on popular cloud platforms like Amazon S3. Currently, DockQR allows for the following execution schemes: (1) Simple execution of the pipeline on one input FITS image with the output written to a designated output directory (2) Complex execution of a workflow sequence defined via a parameter file within the input directory (3) A completely independent pipeline that listens to an Advanced Messaging Queue Protocol (AMQP) server and executes the pipeline as instructed while also passing back status updates to the same AMQP server. While we focus on the Dockerized QuickReduce pipeline container in this paper, the underlying methodology extends to any complex pipeline setup, as illustrated in our StarDock paper, even setups that require legacy codes like IRAF with specific pre-requisites (for example: a specific and an older version of Python that conflicts with an Operating System requirement).

9913-125, Session PS1

The HARPS-N archive through a Cassandra, noSQL database suite

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The TNG-INAF is developing the science archive for the WEAVE instrument. The underlying architecture of the archive is based on a non relational database, more precisely, on Apache Cassandra cluster, which uses a noSQL technology. In order to test and validate the use of this architecture, we created a local archive which we populated with all the HARPS-N spectra collected at the TNG since the instrument's start of operations in mid-2012, as well as developed tools for the analysis of this data set. In our design, Cassandra works side by side Apache Solr (Search engine) and Apache Spark (Real-Time Analytics) for an efficient data indexing, extraction and analysis.

The HARPS-N data set is two orders of magnitude smaller than WEAVE, but we want to demonstrate the ability to walk through a complete data set and produce scientific output, as valuable as that produced by an ordinary pipeline, though without accessing directly the FITS files. The analytics is done by Apache Solr and Spark and the work-load is split up on a cluster. As an example, we produce observables like metallicity indexes for the complete set of the targets in the archive and compare the results with the ones coming from the HARPS-N regular data reduction software.

The aim of this experiment is to explore the viability of a high availability cluster and distributed noSQL database as a platform for complex scientific analytics on a large data set. We additionally want to demonstrate the horizontal scalability of such a system to cope growing processing and storage demands by adding more resources.

9913-131, Session PS1

Virtualizing observation computing infrastructure at Subaru Telescope

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Subaru Telescope, an 8-meter class optical telescope located in Hawaii, has been using a high-availability commodity cluster as a platform for our Observation Control System (OCS). Until recently, we have followed a tried-and-tested practice of running the system under a native (Linux) OS installation with dedicated attached RAID systems and following a strict cluster deployment model to facilitate failover handling of hardware problems (we have a paper on this high-availability cluster design in SPIE Astronomical Telescopes and Instrumentation 2010).

Following the lead and apparent benefits of virtualizing (i.e. running in virtual machines) many of our non-observation critical systems at the base facility, we recently began to explore the idea of migrating other parts of the observatory's computing infrastructure to virtualized systems, including the summit OCS, data analysis systems and even the front ends of various Instrument Control Systems.

In this paper we describe our experience with the initial migration of the Observation Control System to virtual machines running on the cluster and using a new generation tool--ansible--to automate installation and deployment. This change has significant repercussions for ease of cluster maintenance, upgrades, snapshots/backups, risk-management, availability, performance, cost-savings and energy use. In this paper we discuss some of the trade-offs involved in this virtualization and some of the impacts for the above-mentioned areas, as well as the specific techniques we are using to accomplish the changeover and simplify installation and management complexity.

9913-137, Session PS1

Information and Communications Technology (ICT) Infrastructure for the ASTRI SST-2M telescope prototype for the Cherenkov Telescope Array

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In the framework of the International Cherenkov Telescope Array (CTA) project, the Italian National Institute for Astrophysics (INAF) is developing the ASTRI SST-2M end-to-end prototype telescope, which is being installed at the INAF observing station located in Serra La Nave on Mt. Etna, Italy. The ASTRI mini-array, composed of nine of these telescopes, is proposed to be installed at the Southern CTA site.

Among the various infrastructures, the correct Information and Communication Technology (ICT) equipment is necessary to achieve high efficiency in all operations of computing and data storage, as well as control of the entire telescope

Thus a complete and stand-alone computer centre has been designed and implemented. The design goal is to obtain basic ICT equipment, with an adequate level of redundancy, that might be scaled up for the ASTRI mini-array, taking into account the necessary control, monitor and alarm system requirements. This contribution presents the ICT equipment currently installed at the Serra La Nave observing station where the ASTRI SST-2M prototype will operate. The computer centre and the control room are described with particular emphasis on the Local Area Network scheme, the computing and data storage system, and the telescope control and monitoring.

9913-182, Session PS1

Radio data archiving system

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Radio Astronomical Data models are becoming very complex since the huge possible range of instrumental configurations available with the modern Radio Telescopes.

What in the past was the last frontiers of data formats in terms of efficiency and flexibility is now evolving with new strategies and methodologies enabling the persistence of a very complex, hierarchical and multi purpose information.

Such an evolution of data models and data formats require new data archiving techniques in order to guarantee data preservation following the directives of Open Archival Information System and the International Virtual Observatory Alliance directives for the data sharing and publication.

Currently, various formats (FITS, MBFITS, VLBI's XML description files and ancillary files) of data acquired with the Medicina and Noto Radio Telescopes are under storing and handling by a common Radio Archive. It aims at providing the (inter)national community with a state-of-the-art archive for radio astronomical data and delegate as much as possible to the software setting on how and where the descriptors (metadata) are saved, while the users perform user friendly queries translated by the web interface into complex interrogations on the database to retrieve data. In such a way, the Archive is ready to be Virtual Observatory compliant and as much as possible user friendly.

9913-70, Session PS2

Pre-selecting muon events in the camera server of the ASTRI telescopes for the Cherenkov Telescope Array

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As already demonstrated by all existing Imaging Atmospheric Cherenkov Telescopes, the analysis of muon rings is a powerful and precise method to calibrate the optical throughput of each telescope. Due to the variety of telescope types and sizes foreseen in the Cherenkov Telescope Array (CTA) and degradation of the optical elements, differences in efficiency can however be present. While Large and Medium Size telescopes will be able to detect muon images under a stereo trigger, for the Small Size telescopes the stereo muon rate will tend to zero, given their small mirror area and large inter-telescope distance. Nevertheless, fully contained muon rings can be used as calibrators of each individual telescope since they can be efficiently recognized from un-calibrated images in their camera server and flagged as such, even if no stereo coincidence is available. This is the case for the ASTRI SST-2M telescopes, which are able to detect muon events during regular data taking without requiring a dedicated trigger.

In this contribution we present an efficient and fast algorithm to recognize useful single-muon ring images within the ASTRI camera server. The algorithm, applied to uncalibrated but cleaned images, is essentially based on the application of the Taubin method which enables the rapid determination of the geometrical parameters of the circle enclosing the ring (center, radius, ring width). The study has been performed on simulated data starting from the basic telescope configuration of the ASTRI SST-2M end-to-end prototype installed in Italy at the Serra La Nave observing station, and applying the geographical coordinates and atmospheric conditions foreseen for the CTA southern site where nine ASTRI telescopes have been proposed to be installed to form the so-called ASTRI mini-array. The simulation results and the cuts applied on the reconstructed Taubin parameters show that the algorithm achieves more than 90% efficiency for muons while keeping the number of proton-induced triggers as low as possible to minimize useless readout in the CTA array data acquisition system. The events flagged as possible single-muon ring images will then be analyzed in detail during the phase of the off-line scientific and calibration analysis.

9913-74, Session PS2

Automatization of the guiding process in the GTC

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The "Gran Telescopio de Canarias" (GTC) is an optical-infrared 10-meter segmented mirror telescope at the ORM observatory in Canary Islands (Spain). The GTC Control System (GCS) is continuously evolving to enhance the operational efficiency.

In this work we present the new GCS subsystem to automatize the guiding setup process, both for Fast Guiding and for Slow Guiding. Previously, the telescope operator had the responsibility to choose the guide star and to setup the A&G subsystems. Some of these processes are time consuming when performed by a human being. This had an unwanted impact on the operational efficiency.

The new system automatizes all the guide process. A set of restrictions (including photometric computations and vignetting with the main science instrument) are used to select the stars appropriate for guiding. Then a merit function with tunable parameters is used to choose the best one. Finally, the system computes the optical configuration that fits better the selected star, automatically performs the guide star acquisition process and closes the guide loop.

This is the first step of a more extended project that will analyze the operational processes at GTC from a global point of view, and improve them towards a more automatic and efficient system.

9913-78, Session PS2

Wendelstein Observatory control software

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LMU Muenchen operates an astrophysical observatory on the summit of Mt. Wendelstein in the Bavarian Alps. The 2m Fraunhofer telescope (Proc. SPIE 7733, 8444, 9145) is equipped with a 64 Mpixel, 0.5 x 0.5 square degree FoV wide field camera (WWFI, Proc. SPIE 7735, 8446) and a 3 channel optical/NIR camera (3kk, Proc. SPIE 7735 and this conference). Two fiber coupled spectrographs (upgraded Echelle spectrograph FOCES with wavecomb, Proc SPIE 7735, 8446; and IFU spectrograph VIRUS-W, Proc. SPIE 7014, 8446, currently operated at the 2.7 m telescope at the McDonald Observatory in Texas) and a wavefront sensor will be added in the near future. In addition we plan to upgrade the observatory's 40cm telescope and its camera and spectrograph for the students lab. The observatory also hosts a multitude of supporting hardware, i.e. allsky cameras, webcams, meteostation, air conditioning etc. All scientific instruments and related hardware are monitored by and can be controlled through a single, central "Master Control Program" (MCP). Here we explain concept and implementation of the MCP as a multi-threaded Python daemon in the area of conflict between debugability and DRY (don't repeat yourself). The MCP has been built to enable complex automated observations schemes. It supplies meta data for scientific data containers (i.e. FITS keys) and can be used to trigger simple quicklook, calibration, or even full-fledged data reduction processes.

9913-82, Session PS2

Integration of the instrument control electronics for the ESPRESSO spectrograph at ESO-VLT

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ESPRESSO, the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations of the ESO - Very Large Telescope site, is now in its integration phase.

The large number of functions of this complex instrument are fully controlled by a Beckhoff PLC based control electronics architecture.

Four small and one large cabinets host the main electronic parts to control all the sensors, motorized stages and other analogue and digital functions of ESPRESSO. The Instrument Control Electronics (ICE) is built following the latest ESO standards and requirements. Two main PLC CPUs are used and are programmed through the TwinCAT Beckhoff dedicated software.

The assembly, integration and verification phase of ESPRESSO, due to its distributed nature and different geographical locations of the consortium partners, is quite challenging.

After the preliminary assembling and test of the electronic components at the Astronomical Observatory of Trieste and the test of some electronics and software parts at ESO (Garching), the complete system for the control of the four Front End Unit (FEU) arms of ESPRESSO has been fully assembled and tested in Merate (Italy) at the beginning of 2016.

After these first tests, the system will be sent to the Genéva Observatory (Switzerland) for the Preliminary Acceptance Europe (PAE) and finally shipped to Chile for the commissioning.

This paper will describe the integration strategy of the ICE workpackage of ESPRESSO, the hardware and software tests that have been performed, with an overall view of the experience gained during these project's phases.

9913-86, Session PS2

The ICT monitoring system of the ASTRI SST-2M prototype proposed for the Cherenkov Telescope Array

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In the framework of the international Cherenkov Telescope Array (CTA) observatory, the ASTRI Consortium, lead by the Italian National Institute for Astrophysics (INAF) has developed the ASTRI SST-2M end-to-end prototype. It is installed at the INAF observing station located at Serra La Nave on Mt. Etna, Italy. The ASTRI mini-array, composed of nine of these telescopes, is proposed to be installed at the Southern CTA site. This contribution presents the solutions implemented to realize the monitoring system for the Information and Communication Technology (ICT) infrastructure of the ASTRI-SST-2M prototype.

The ASTRI ICT monitoring system has been implemented by integrating traditional tools, used in the computer centre, with specific custom tools which interface via Open Platform Communication Unified Architecture (OPC UA) to the Alma Common Software (ACS) that is used to operate the ASTRI-SST-2M prototype. The traditional monitoring tools are based on Simple Network Management Protocol (SNMP) and commercial solutions and features embedded in the devices themselves. They generate alerts by E-mail and SMS. The specific custom tools convert the SNMP protocol into the OPC UA protocol and implement an OPC UA server. The server interacts with an OPC UA client implemented in an ACS component that, through the ACS Notification Channel, sends monitor data and alerts to the central console of the ASTRI-SST-2M prototype. The same approach has been proposed also for the monitoring of the CTA on-site ICT infrastructures.

9913-90, Session PS2

Challenges and strategies for the maintenance of the SKA telescope manager

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The Square Kilometre Array (SKA) is an ambitious project to build a radio telescope that will enable breakthrough science and discoveries, not possible with the existing facilities, over the next 50 years.

This huge facility, composed by a set of specific elements (e.g. Dishes, Low-Frequency Aperture Arrays, Signal and Data Transport, Infrastructure), will be orchestrated by a core element, Telescope Manager (TM), aimed to coordinate observation scheduling and management, collect health and performance data from the Elements and interface with external operators. TM will be mostly a software-based system, running on a dedicated hardware, that will interact with a large set of external units, represented

by the Local Monitoring and Control systems (LMCs) of the SKA Elements, composed in turn by hardware and software systems.

Given the large lifespan for the project, the evolution in hardware and software, both for TM itself and for the LMCs, is expected to generate a continuously-, and perhaps dramatically-changing environment which will need a deep analysis in terms of maintenance.

Considering TM software, in particular, new requirements are expected to emerge, old requirements could change during application lifetime, errors will be discovered or performance will need to be improved: software maintenance is therefore critical to maintain the value of the software developed.

In this paper the strategy of maintenance for both TM hardware and software is presented. The four main areas of such a plan, Maintenance Process, Organization, Resources and Performance tracking are described in detail.

9913-94, Session PS2

The technical CCDs in ESPRESSO: usage and performance

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The Echelle SPectrograph for Rocky Exoplanets and Stable Spectral Observations (ESPRESSO), built for the ESO Very Large Telescope at Paranal (Chile), requires active–loop stabilization on both the pupil and field images. This is accomplished by using components off-the-shelf (COTS) cameras to acquire the images, a custom algorithm to find the center of the fiber feeding the spectrograph, and piezoelectric actuators to correct the light beam. A further camera is required to monitor the amount of light collected by the scientific detectors (exposure meter). Therefore, in the most demanding configuration (4 telescopes), ESPRESSO will use up to 9 cameras and 8 piezo actuators simultaneously.

The ESPRESSO control software and the VLT-Technical Detector Control Software (TDCS, developed at ESO) works in conjunction to pursue such a challenging task, and the experience gained during ESPRESSO integration will be used also on future ESO instruments.

In this work we discuss the optimal technical CCD configuration and usage, the overall system performance and the network bandwidth requirements for the ESPRESSO operations.

9913-98, Session PS2

The SKA observation control system

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The Square Kilometre Array (SKA) will be the world's most advanced radio astronomy observatory, designed to be many times more sensitive and hundreds of times faster at mapping the sky than current facilities. The first phase of the SKA will be delivered in the form of two telescopes: a 200-element dish interferometer in South Africa and a 130000-element dipole antenna aperture array in Australia.

The scale and requirements of the SKA present new challenges in the area of observation control. Firstly, the SKA is designed from the outset to maximise observing efficiency by allowing multiple concurrent observations. The observation control system must facilitate, co-ordinate and control each observation while remaining responsive and retaining overall control.

Secondly, with so many hardware elements present in each SKA telescope, a more intelligent approach to failures must be used; observations should not be terminated on every hardware failure, but only those that mean the science goals cannot be achieved. This requires a continuous assessment of the science capabilities that the active hardware configuration offers, and how the failure of an element impacts those capabilities.

Observing sequences can also be controlled and altered in real time, for example, to accommodate the calibration needs of the telescope or to urgently switch to a Target of Opportunity. Achieving this while still presenting a predictable and accessible interface to astronomers is another challenge that the SKA observation control system must face.

This poster will give an overview of the SKA Observation Execution function and how its design will address these challenges.

9913-102, Session PS2

Rejecting harmonic vibrations at Gemini with real-time vibration tracking

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Fighting vibrations on large telescopes is an arduous task. At Gemini, vibrations originating from cryogenic coolers have been shown to degrade the optical wave front, in certain cases by as much as 40%. This paper discusses a general solution to vibration compensation by tracking the real time vibration state of the telescope and using M2 to apply corrections. Two approaches are then presented: an open loop compensation at M2 based on the signal of accelerometers at the M1 glass, and a closed loop compensation at M2 based on optical measurements from the wave front sensor. The paper elaborates on the pros and cons of each approach and the challenges faced during commissioning. A conclusion is presented with the final results of vibration tracking integrated with operations.

9913-109, Session PS2

Research on measurement and control technology of active reflector for FAST

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The active reflector is a sphere with a diameter of 500 meters and a radius of 300 meters, which is composed of a main body supporting structure, an actuator, a back frame and a reflective panel. The active variable is the biggest characteristic of the FAST reflector, and the 300m aperture is formed in the observation direction by controlling the 2225 actuators along the radial motion. The observing paraboloid is moving along with observation area at a range of 500m diameter spherical, so as to achieve the following observation.

The overall technical indicators of active reflector as follows, reflecting surface profile accuracy requirements outgo RMS 5mm; The source changing time less than 10 minutes; The actuator adjusting speed is faster than 1.6mm/s; Paraboloid pointing angle range from - 40 deg to 40 deg.

In order to ensure the safe and accurate operation of the reflective surface system, The main reflective surface control system, the reflective surface

measurement system and the reflective surface health monitoring system need to work together.

Active reflector control system mainly form precise position and accurate parabolic surface by adjusting the actuating elongation of reflector node position according to astronomical target trajectory planning and measurement data. In order to realize the control target, the software of control algorithm?the reliability and the real-time performance of the communication and the effective storage and management of the data need to be developed.

In the operation of the telescope, the measurement of the different total station instrument is carried out by the computer. The time of measurement within the effective aperture is less than 10 minutes, and then the measurement results are transmitted to the control system in real time.

The main reflective surface health monitoring system is used to ensure the safety, integrity, applicability and durability of the structure by monitoring the internal force, structural deformation and other parameters of the structure and evaluating the safety level of structure on the basis of regular monitoring data and structural environment load monitoring data.

9913-112, Session PS2

LSST OCS status and plans

Philip N. Daly, German Schumacher, LSST (United States)

The Large Synoptic Survey Telescope (LSST) received construction funding in 2014, on an 8.3 years construction and commissioning schedule. The LSST is a complex system of systems with demanding performance and operations requirements. A critical component of the LSST Telescope and Site software is the Observatory Control System (OCS), that comprehends the master control system that schedules, coordinates, commands and monitors the observatory. This poster reports progress on the OCS and outlines future development plans.

9913-115, Session PS2

Motion planning techniques for MIRADAS robotic probe arms

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Many of the leading scientific challenges in modern Astrophysics can only be addressed in an efficient manner with the use of moderate to high spectral resolution instruments mounted in large collecting area telescopes. Therefore, the demand for instruments with multiple-object spectrography (MOS) capabilities has significantly increased in the last years as they are indispensable for answering many of the unresolved questions in several research fields. The Mid-resolution InfRAreD Astronomical Spectrograph (MIRADAS) is a near-infrared MOS for Gran Telescopio Canarias, which is able to concurrently observe up to 20 targets at a variety of user-defined locations. This task is performed by 20 independent and deployable Integral Field Units (IFU) based on robotic probe arms with pick-off mirrors. As these arms move in a very cluttered environment, one of the key points of the instrument control system is to plan collision-free trajectories for all the arms.

Traditionally, scientists have followed two different approaches to coordinate the motions of multiple robots: coupled and decoupled. Coupled strategies might be guaranteed to find optimal collision-free motions as they consider the full search space. However, their complexity exponentially increases with the number of robots. On the other hand, decoupled approaches try to reduce the computational costs by seeking solutions in search spaces of lower dimensionality. These algorithms are frequently faster, but, unfortunately, they are not complete and might not find a safe motion plan even though it exists. In this document, we present the particular decoupled approach adopted in the final design review (FDR) of MIRADAS, which took place in the first semester of 2015. The problem of finding collision-free motions basically consist of three distinct steps: paths generations, determining of the coordination groups and, finally, velocity tunning of the paths of each coordination group. In the first stage, suitable paths are independently generated for each arm, then interaction between arms are considered and after, in the last stage, the velocities of the arms are properly adjusted to avoid collisions. This solution takes into account and is heavily influenced by the severe motion constraints imposed by the industrial off-the-shelf cryogenic electronic controllers that drive the stepper motors present in the arm joints. Finally, we also present a coupled approach that has been currently explored in order to determine its computational feasibility and performance.

9913-118, Session PS2

GHOST and GIAPI: experience using Gemini's new instrument control system framework

Peter J. Young, Jon Nielsen, The Australian National Univ. (Australia)

The new Gemini High Resolution Optical Spectrograph (GHOST) will be controlled with software developed against the new Gemini software framework - the Gemini Instrument Application Programmer Interface (GIAPI). The developers describe their experience using this framework and compare it to control systems developed for earlier Gemini instruments using the original Gemini Core Instrument Control System (CICS) framework.

9913-121, Session PS2

Using muon rings for the optical calibration of the ASTRI telescopes for the Cherenkov Telescope Array

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Ring images generated from high-energy muons constitute a very useful tool to calibrate the total optical throughput of any telescope forming the Cherenkov Telescope Array (CTA). Differences in precision and efficiency can however be present due to the variety of telescope types and sizes. The preliminary results of the detailed study described in this contribution show that a set of high-quality muon ring images can be collected by the ASTRI small-size dual-mirror (SST-2M) telescope.

The study was performed starting from the basic configuration of the ASTRI SST-2M prototype installed in Italy at the Serra La Nave observing station. The prototype is able to reconstruct muons with energy greater than 20 GeV with a precision on the direction reconstruction of the order of the pixel size in the ASTRI SST-2M camera (0.17 degrees). The results will be validated from the analysis of real data acquired after the Commissioning Phase of the prototype.

Better quality images will be provided by the new silicon photomultipliers used for the nine ASTRI SST-2M telescopes that will form the ASTRI mini-array proposed to be installed at the final CTA southern site thanks to their higher detection efficiency and a strong reduction of optical cross talk and after pulsing.

9913-124, Session PS2

Weather stations of the ALMA Observatory

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The physical area covered by the ALMA Observatory requires a series of weather stations which provide valid measurements for the online calibrations and corrections used during scientific observations. These weather stations are deployed strategically to deliver valid corrections for antennas located nearby. The first meteo station was installed at the beginning of the construction phase (2007) and recently the last sets were deployed in preparation to the Long Baseline Campaign. A total of 11 sets of weather stations were deployed according to the original design. Each weather station contains 7 sensors which are sampled at 1 Hz, totaling 6.6M of measurements being persisted in daily basis.

In this paper we present the software architecture of the weather station subsystem, which was built on top of the Internet Communication Engine (ICE), an open source distribute programming framework provided by Zeroc Inc. This framework provides binding to C/C++, Java, Python and PHP among others, which allow us to choose the most appropriate programming language for data acquisition, hardware devices life cycle control, data persistent layer and web interface. Publish & subscribe service named IceStorm are used in this design to distribute sampled data among several processes. Additionally services such as IceBox, IceGrid facilitate the deployment aspects. Finally, a mechanism to communicate between ICE and ALMA Common Software (ACS) was implemented to provide weather data to the control observation software.

Measurements of each weather stations are not only used for the scientific observations but also useful for planning of other entities in the observatory, which generate queries in the platform that is not easy to predict. To avoid unexpected delay and provide deterministic responses, a cache mechanism based on Redis was introduced. In addition, due to the amount of samples generated in daily basis, the original design using a relational database was causing difficulties in the maintenance aspect. Given the special nature of this kind of data, in which samples are already sorted at the moment of insertion and typical queries are based on a range of data instead of a single sample associated to a timestamp, we explored non-SQL alternatives to persist the data.

9913-127, Session PS2

INO340 telescope control system: mount control system

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The INO340 stands for Iranian National Observatory, which is an Alt-Az reflecting optical telescope with 3.4m main mirror diameter. The telescope's field of view is 0.3° and the designed F?ratio is f/11. At the moment conceptual design of Telescope is finished and the detail design of the Telescope is developing. The Telescope will be placed in Peak of Gargash Mountain near Kashan City. The result of Microthermal and seeing measurements shows the site can deliver high image quality thus the good image quality is defined as a priority in the telescope design.

The INO340 Control System (INOCS) is responsible for delivering the light from an object to the science instruments. It performs so by controlling all available mechanisms and optical elements according to specified requirements in the presence of specified disturbances. INOCS provides suitable user interface means for obtaining the observe information from scientists and also user interface means for telescope operation in defined modes.

The INOCS comprises the following systems: Observation Monitoring System (OMS), Telescope Control System (TCS), Interlock System (ILS) and Observation System Supervisor (OSS). All systems include necessary electronic, hardware and software components as well as computers and network components. INOCS includes the network infrastructure necessary for communication between its systems.

OSS and OMS subsystems have been explained in other related papers of INO340 and they are out of the scope of this paper. However, Telescope Control System (TCS) of INO340 has not been discussed in details in any relevant papers till now. TCS is responsible for the control of the telescope structure with its mirrors and the dome including 4 major subsystems: Telescope Control System Supervisor (TCSS), Mount Control System (MCS), Active Optics System (AOS). The purpose of this paper, is to present the details architecture of TCS and to discuss one of the major subsystem of TCS called MCS. AOS and TCSS as other major subsystems of TCS will be discussed in future.

The MCS is responsible for pointing and tracking of the main axes and rotator of the telescope and controlling the auxiliary system for mirror cover and cable wrapping. An anti-backlash gear based mechanism using two servomotors applying force against each other is being selected to drive the main Alt and Az axes. The simulations will show the performance of the designed system and will help us to define the specifications of the required elements.

This paper first presents the TCS architecture of INOCS, and then it focuses on the requirements and the major functionalities of MCS. In next section of paper, we provide different analysis of MCS using related parameters such as wind effect, encoder resolution and etc. Then, based on the simulation results the optimum sets of parameters and functions of different modules are concluded. In last section of paper, we present final design of MCS and evaluate the results based on the pre-defined requirements. In addition, the final tracking accuracy over time with the presence of different disturbances is provided.

9913-130, Session PS2

Status, upgrades, and advances of RTS2: the open source astronomical observatory manager

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RTS2 is an open source observatory control system. Being developed from early 2000, it continue to receive new features in last two years. RTS2 is a modulat, network-based distributed control system, featuring telescope drivers with advanced tracking and pointing capabilities, fast camera drivers and high level modules for "bussinees logic" of the observatory, connected to a SQL database. Running on all continents of the planet, it accumulated a lot to control parts or full observatory setups.

9913-133, Session PS2

Using Robotic Operating System (ROS) to control autonomous observatories

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Observatories are complex systems requiring the integration of numerous devices (dome, telescope, instruments, environment sensors, etc.) into a common control system. This is specially challenging in autonomous observatories, where intelligent and coordinated responses are required to solve unexpected situations, either due to the environment (e.g., weather) or to instrumental requirements.

The field of robotics has similar challenges. In a robot, all the sensors have to work together in order to allow the robot to react to any unforeseens or being able to adapt to a new environment. In addition, the field of robotics has experienced a huge growth during the last years, partly due to cheaper hardware and partly due to the appearance of open-source platforms. In this sense, the Robot Operating System (ROS), supported by the Open Source Robotics Foundation, has become one of the most widely used open-source platforms for robot control. The ROS environment allows the integration of any kind of robots, from amateur home-made robots to those requiring the most strict industrial standards, and even for robots in space.

Nowadays, several autonomous observatories are successfully operating worldwide. However, the process of building a new autonomous observatory usually requires a long software development process where all the different devices have to be integrated into a common platform. The large flexibility of ROS, together with the large community behind it, encouraged us to develop a new ROS package to control observatories. We pursue three main goals with this new package. Firstly, to prove that autonomous observatories can be successfully controlled using ROS. Secondly, to provide the observatory with a decision making procedure based on automated planning and scheduling. Finally, to introduce a simple, well tested and widely distributed platform into the world of autonomous observatories.

The current version of our new ROS package integrates several commercial devices to create a fully autonomous observatory. The observatory is composed by a Baader Planetarium dome, a Meade telescope, a SBIG camera and a Boltwood sensor for environment monitoring. All systems are integrated into ROS through custom-made drivers. The autonomous response of the observatory is provided by OpenROCS (Colomé et al., SPIE, 2012) which implements all the required know-how to make the observatory operation both safe and operationally optimal, communicating with all the different devices thanks to ROS.

The combination of OpenROCS and ROS is opening a new window for autonomous observatories. Creating a new observatory autonomous will no longer require a long software development process. It can be easily integrated into the regular construction of a new observatory without additional overheads.

9913-136, Session PS2

On-board target acquisition for CHEOPS

Philipp Loeschl, Roman Ferstl, Franz Kerschbaum, Roland Ottensamer, Univ. Wien (Austria)

The CHaracterising ExOPlanet Satellite (CHEOPS) is the first ESA S-class and exoplanetary follow-up mission headed for launch in 2017. It will perform high-precision photometry of stars hosting confirmed exoplanets, whereas V-magnitudes range from 6 to 12. Besides the identification of the presence of significant atmospheres down to Earth-sized planets, its mission goals include measurements of radii for hot Neptune planets and energy flux determinations for hot Jupiter planets, while also looking for unknown co-aligned smaller mass planets.

The CHEOPS payload instrument is a 32cm telescope with a passively cooled optical CCD. The star images are defocused (12 pixels radius) to mitigate the effect of individual pixels. Only a single target star is observed at a time, which needs to be centred and guided with high precision within a 200x200" window on the CCD. As a result of CHEOPS' structural design, there is an uncertainty between the alignment of its star trackers and the payload instrument telescope due to thermal deformations, resulting in an absolute pointing error of up to 120". Additionally, the rotation rate of CHEOPS' field of view is 4 degrees per minute, consequently the initial identification must be rotation invariant. In order to guarantee the autonomous identification of the target star and to infer the corrections of the pointing for the attitude and orientation control subsystem (AOCS), a special target acquisition algorithm is included in the instrument flight software (IFSW). This software is developed by the University of Vienna for the data processing unit (DPU). Its tasks are instrument control, health monitoring and on-board data processing. The processing tasks include data compression steps, live centroid calculation for fine-guiding and the initial target acquisition, which will be described in detail in this paper.

The target acquisition system will deal with star densities varying from empty fields containing only the target to crowded fields where stars may partly overlap. The star identification requires an initial source extraction, followed by an identification algorithm suitable for solving the current star configuration. Besides the trivial single star case, we investigated two main approaches for the identification problem. The nominal algorithm is a modified Liebe (Liebe et al. 1993), which operates through the extraction of inter-star angles and distances. The second algorithm (Padgett et al. 1997) is based on pattern recognition for certain star constellations.

Both algorithms compare the parameters derived from the image with a predefined dataset, specifically created for each observation on ground. As the uplink is highly limited, these datasets need to be smaller than 1 kiB. It is crucial for the star identification to be fully reliable and autonomous, as science operation outside of communication windows is required.

Only a limited share of the DPU resources is available for the star identification task. Hence the implemented algorithms are optimised for fast processing. In order to evaluate the algorithms' reliability, thousands of random star configurations were analysed in Monte-Carlo simulations.

We present the performance results as well as recommended parameters that guarantee a successful identification under all conditions.

9913-139, Session PS2

Towards integrated modeling: full image simulations for WEAVE

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We present an integrated end-end simulation of the spectral images that will be obtained by the WEAVE spectrograph, which aims to include full modelling of all effects from the top of the atmosphere to the detector. These data are based in input spectra from a combination of library spectra and synthetic models, and will be used to provide inputs for an end-end test of the full WEAVE data pipeline and archive systems, prior to 1st light of the instrument.

9913-140, Session PS2

Cherenkov Telescope Array science data analysis using the c-tools

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The ctools are an open source software package developed for the scientific analysis of Imaging Air Cherenkov Telescope data. This includes data from existing telescopes, such as H.E.S.S., VERITAS and MAGIC, and the upcoming data of the Cherenkov Telescope Array (CTA). ctools are comprised of a set of ftools-like binary executables with a command-line interface for interactive step-wise data analysis, and a Python module that exposes all executables as Python classes. Extensions of the ctools package by user-defined binary executables or Python scripts is supported. A first stable version of the ctools package has now been released. We will present the package to the community and illustrate its capabilities by means of typical analysis examples.

9913-141, Session PS2

SKA CSP monitor and controls: technological challenges

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The Square Kilometer Array (SKA) project is an international effort to build the world's largest radio telescope, with eventually over a square kilometer of collecting area. For SKA Phase 1, Australia will host the low-frequency instrument with more than 500 stations, each containing around 250 individual antennas, whilst South Africa will host an array of close to 200 dishes. The scale of the SKA represents a huge leap forward in both engineering and research and development towards building and delivering a unique instrument, with the detailed design and preparation now well under way. As one of the largest scientific endeavors in history, the SKA will brings together close to 100 organizations from 20 countries.

Every aspect of the design and development of such a large and complex instrument requires state-of-the-art technology and innovative approach.

This poster addresses some aspects of the SKA monitor and control system, and in particular describes the development and test results of the CSP Local Monitoring and Control prototype.

At the SKA workshop in April 2015, SKA monitor and control community has chosen TANGO Control System as a technology of choice for the implementation of the SKA monitor and control. This decision will have a large impact on Monitor an Control development of SKA. As work is on the way to incorporate TANGO Control System in SKA, we have started a prototype development for the SKA Central Signal Processor to mitigate the associated risks. In particular we now have developed a uniform class schema proposal for the sub-Element systems of the SKA-CSP.

9913-143, Session PS2

Remote observing environment using a KVM-over-IP for the OAO 188 cm telescope

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We have prepared remote observing environment for the 188 cm telescope at Okayama Astrophysical Observatory in which a KVM-over-IP is employed to redirect displays and keyboards to remote sites. The operation through the remote console is almost indistinguishable from that through the on-site telescope console. The environment was opened for common-use since 2015, more than 10 groups have experienced remote observation. No serious trouble due to the KVM-over-IP has reported so far. In this paper we will present specification, configuration of the hardware as well as performance evaluated through the actual observations.

Okayama Astrophysical Observatory is a branch of National Astronomical Observatory of Japan. The observatory has a 188 cm reflector manufactured in 1960 by Grubb & Parsons, England, and three observatory instruments which are capable of optical high resolution spectroscopy (HIDES), optical imaging and low resolution spectroscopy (KOOLS) and near infrared imaging and low to medium resolution spectroscopy (ISLE).

We have prepared the remote observing environment for the telescope aiming for better use of the facility and to increase the products.

KVM-over-IP is a network device to redirect target PC's displays, mice and keyboards to a remote site over internet. We selected Dominion-KX III 808 from Raritan for the KVM-over-IP, which can be a host of eight target PCs and offers simultaneous access from eight remote console for every targets. Host PCs, such as for telescope or instruments consoles, are connected to the KVM-over-IP via dedicated adopters and UTP cables.

The use of the remote observing environment is easy. An authorized observer can make a remote observation by three steps: the user first establish the VPN connection to the observatory sub-net, login the KVM-over-IP via an internet browser, and click the target PC to be used from the list of targets on the browser. Then the selected on-site console appears on the local console. The KVM-over-IP can transfer digital sound over internet by default. Remote observers listen the sound of dome rotation, telescope slewing or alert voice on status change via remote speaker attached to the local PC.

VNC technique has been widely used to build remote observing environment and the application of KVM-over-IP will be rare case. However, KVM-over-IP is advantageous in many aspects. The remote observer will not be forced to install a dedicated software. T the maintenance effort is quite low, just upgrade the firmware prepared by the vendor. KVM-over-IP can manage users so that an administrator can grant access right to observers of a certain night. The function is quite useful to maintain the information security of observers, and no VNC software does not support the function as long as we know.

9913-144, Session PS2

The Cherenkov Telescope Array Observatory top-level use cases

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Today the scientific community is facing an increasing complexity of the scientific projects, from both a technological and a management point of view. The reason for this increase is in the advance of science itself, where new experiments with unprecedented levels of accuracy, precision and coverage (time and spatial) are realised. Astronomy is one of the fields of the physical sciences where a strong interaction between the scientists, the instrument and software developers is necessary to achieve the goals of any Big Science Project. The Cherenkov Telescope Array (CTA) will be the largest ground-based very high-energy gamma-ray observatory of the next decades. To achieve the full potential of the CTA Observatory, the system must be put into place to enable users to operate the telescopes productively. The software will cover all stages of the CTA system, from the preparation of the observing proposals to the final data reduction, and must also fit into the overall system. Scientists, engineers, operators and others will use the system to operate the Observatory, hence they should be involved in the design process from the beginning. We have organised a workgroup and a workflow for the definition of the CTA Top Level Use Cases in the context of the Requirement Management activities of the CTA Observatory. Scientists, instrument and software developers are collaborating and sharing information to provide a common and general understanding of the Observatory from a functional point of view. Scientists that will use the CTA Observatory will provide mainly scientifically driven Use Cases, whereas technical people will subsequently provide more detailed Use Cases, comments and feedbacks. The main purposes are to define observing modes and strategies, and to provide a framework for the flow down of the Use Cases and requirements (from general to detailed Use Cases and specifications) to check missing requirements and the already developed Use-Case models at CTA sub-system level. The Use Cases will also provide the basis for the definition of the Acceptance Test Plan for the validation of the overall CTA system. In this contribution we present the organization and the workflow of the workgroup.

9913-145, Session PS2

Remote operations at UKIRT, Cassegrain included, 2 years later

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UKIRT has been operated remotely with only WFCAM since 2010. Since UKIRT was acquired by new owners it was pursued to also operate the Cassegrain instruments again, but stay with remote operations.

The first remotely operated Cassegrain block at UKIRT took place in the summer of 2014 and we got to the end of its 3rd remotely operated Cassegrain block in November 2015. For the first one we only operated short infrared instruments UFTI and UIST, for the second and third also mid-infrared imager/spectrometer Michelle that we hadn't had available since 2004. Between the Cassegrain blocks we of course switched back to WFCAM operations. Building on the experience already gained with operating remotely with WFCAM, remote Cassegrain operations turned out not too big a deal.

9913-147, Session PS2

Agile development approach for the observatory control software of the DAG 4m telescope

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Observatory Control Software for the upcoming 4m infrared telescope of DAG (Eastern Anatolian Observatory in Turkish) is in the beginning of its lifecycle. After the process of elicitation-validation of the initial requirements, we have been focused on preparation of a rapid conceptual design not only to see the big picture of the system but also to clarify the further development methodology. The existing preliminary designs for both software (including TCS and active optics control system) and hardware shall be presented here in brief to exploit the challenges the

DAG software team has been facing with. The potential benefits of an agile approach for the development will be discussed depending on the published experience of the community and on the resources available to us.

9913-149, Session PS2

The CARMENES instrument control software suite

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The main goal of the CARMENES instrument is to perform high-accuracy measurements of stellar radial velocities (1 m/s) with long-term stability. CARMENES is installed at the 3.5 m telescope in the Calar Alto Observatory (Spain) and it is equipped with two spectrographs covering from the visible to the near-infrared. The fundamental science objective of CARMENES is to carry out a survey of ?300 late-type main-sequence stars with the goal of detecting low-mass planets in their habitable zones. It uses its near-IR capabilities by observing late-type stars, whose peak of the spectral energy distribution falls in the relevant wavelength interval. We present the software packages that are included in the instrument control layer. The coordination and management of CARMENES is handled by the Instrument Control System (ICS), which is responsible for carrying out the operations of the different subsystems providing a tool to operate the instrument in an integrated manner from low to high user interaction level. The ICS interacts with the following subsystems: the near-infrared (NIR) and visible channels, composed by the detectors and exposure meters; the calibration units; the environment sensors; the front-end electronics; the acquisition and guiding module; the interfaces with telescope and dome; and, finally, the software subsystems for operational scheduling of tasks, data processing, and data archiving. All the software packages run in a coherent infrastructure that uses the CARMENES protocol and the Internet Communications Engine (ICE) and EPICS frameworks for secure and reliable communication among subsystems. The control suite that implements the CARMENES operational design is integrated in the instrument since the end of 2015. The CARMENES workflow covers from the translation of the survey strategy into a detailed schedule to the data processing routines that extract radial velocity data from the observed targets. The software control framework and all the software modules and layers for the different subsystems contribute to maximize the scientific return of the instrument. The control software enables the efficient and dynamic reaction to schedule the observations with both NIR and visible channels by combining the static constraints that are known a priori (i.e., target visibility, sky background, required periodogram coverage) and the dynamic change of the system conditions (i.e., weather). We also present the graphical user interface and the software validation process, together with the analysis of the first season performance taking into account the key indicators for the first months of operation. Finally, the software engineering procedures implemented that guaranteed the project success are discussed.

9913-151, Session PS2

Target-based fiber assignment for large survey spectrographs

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Next generation fiber-fed massive spectroscopic survey projects have to process a massive amount of targets and assign these to their fiber positioners. To ensure that the preparation of subsequent observations are feasible in a reasonable amount of time, quick target assignment is essential. Existing fiber assignment algorithms, for example the drainage algorithm by Morales et al., concentrate primarily on optimizing fibre positioner usage but remain computationally heavy for efficient target assignment at high target densities. These algorithms also produce target solutions, which may present additional challenges for the path-finding problem. Therefore ensuring that the assigned targets could be reached without collisions and deadlock would result an important gain of efficiency.

Therefore we will present a fast algorithm for target assignment for the next generation of massive spectroscopic survey projects using fiber positioner robots. This algorithm is designed, given a vast number of targets, to be able to assign targets to positioners quickly and with the least loss in the assignment efficiency. The proposed algorithm uses a target-based approach which reduces the complexity of the algorithm to O(log(n)). This paper provides details about the characteristics of the algorithm and how and when to use it for optimal survey strategies. We also investigate optimization methods for the "ease of path-finding" with the goal to reduce the number of situations of impossible path finding problems therefore improving overall coverage efficiency.

Improving the usability and the efficiency of the pre-observation software should result in smooth and efficient operating of fiber-fed massive spectroscopic survey projects considerably.

9913-153, Session PS2

The 4MOST facility control software

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The 4MOST (4 m Multi-Object Spectrographic Telescope) Consortium will be running spectroscopic all-sky public surveys on the ESO VISTA telescope at Paranal Observatory expected to begin in 2019. Two low-resolution spectrographs at R ~ 5000 covering the wavelength range between about 390 and 950 nm and one high-resolution spectrograph at R ~ 18000 operating at 392.6-436.5 nm, 521-571 nm and 606-675 nm or 612-681 nm will be fed by approximately 2400 fibres. Both types of spectrographs will be fixed-configuration, three-channel spectrographs. The instrument utilises the tilting spine Echidna concept to simultaneously obtain spectra of about 2400 independent objects, distributed over an hexagonal field-of-view of four square degrees.

This paper aims at giving an overview of the control software design, which is based on the standard ESO VLT software architecture and customised to fit the needs of the 4MOST instrument. In particular, the facility control software is intended to arrange the precise positioning of the fibres, to schedule and observe many surveys in parallel, and to combine the output from the three spectrographs.

In order to avoid performance bottlenecks, the system is divided into three subinstruments: the main system QMOST which contains the Supervisory Observation Software (SOS) and interfaces with the telescope control software, QMOSTS controlling the spectrograph functions and QMOSTP responsible for the fibre positioner. The SOS process will control the observation software of the two other subsystems. The observation

sequences in 4MOST will be designed to use spectrographs in parallel with synchronous points for the data exchange between the individual subinstruments. To minimise instrument reconfiguration overhead, the fibres are repositioned while the telescope acquires a new field. This procedure requires a complex choreography of telescope and the entire instrument in order to align various actions in the most time-efficient way.

Under the continuous movement of the telescope during science exposures, changes in the gravity vector may result in a flexure of the fibres. To compensate, a secondary guiding system will be implemented that is driven by up to twelve 7-core fibre bundles mounted on spines as well.

Moreover, 4MOST's software will include user-friendly GUIs that enable the night observer to interact with the facility control system and to monitor all data-taking and calibration tasks of the instrument.

In order to control hardware devices, Programmable Logic Controller (PLC) components will be used, following the new fieldbus extension standard for future instruments at ESO.

9913-156, Session PS2

Modified deformable mirror stroke minimization control for direct imaging of exoplanets

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For direct imaging of faint exoplanets, coronagraphs are widely used to suppress light and achieve a high contrast. Wavefront correction algorithms based on adaptive optics are introduced simultaneously to mitigate aberrations in the optical system. Stroke minimization is one of the common control algorithms used for high-contrast wavefront control. This technique calculates the minimum deformation across the DM's surface under the constraint that a targeted contrast level in the search area is achieved, namely the dark hole. In this paper we present a modified stroke minimization algorithm. Instead of using single constraint on intensity averaged over all pixels, we constrain the intensity of each pixel in the dark hole. By introducing auxiliary variables, we switch to an inequality constraints from the equality constraints. Using numerical simulation, we find that the revised algorithm leads to a more uniform dark hole and faster convergence. We also show experimental results of the new control algorithm from the Princeton High-Contrast Imaging testbed.

9913-158, Session PS2

The instrument control software package for the Habitable-zone Planet Finder spectrometer

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The Habitable-zone Planet Finder (HPF) spectrograph will enable precise radial velocity searches for low-mass planets orbiting M-dwarfs, and will be installed on the Hobby-Eberly Telescope (HET) in 2016. We have constructed a novel Instrument Control Software (ICS) package for HPF to control and monitor instrument subsystems, facilitate communication with the HET, and provide user interfaces for observers and telescope operators. The core of the ICS is the asynchronous messaging router, which uses the network software stack provided by the Python Twisted engine, and runs on a CentOS Linux platform. This infrastructure provides a modern, object-based, event driven backbone that is fault resistant and easily extensible to additional hardware or even other instruments. Instrument subsystems communicate through a suite a custom software protocols, primarily written in Python. Bi-directional communication with the HET is enabled directly through network protocols built into the backend. We have created two front-end interfaces to the ICS: a command-line system built in Python, which provide direct access to all ICS functionality; and a modern, graphical Qt interface to provide the regularized interaction desired by observers and telescope operators. We will describe the core frontend and backend systems.

In addition, we will describe several of the customized subsystem communication protocols that provide access to and help maintain the numerous hardware systems that comprise HPF. In particular, we will show how asynchronous communication benefits the numerous hardware components that make up the Environmental Control Subsystem and facilitate HPF's exquisite temperature and pressure control. We will also discuss our Detector Control Subsystem, built as a set of custom Python wrappers around the linux-based c-library that provides native access to the SIDECAR Asic and Hawaii-2RG detector system used by HPF. HPF will be one of the first astronomical instruments on-sky to utilize this native linux capability.

The flexible nature of the HPF ICS makes it easily adaptable to other astronomical instruments. Such code reuse has the potential to provide significant cost and schedule savings, while also reducing operational risk with a field tested backend. The Penn State instrument concept for NASA's Extreme Precision Doppler Spectrometer for the WIYN Telescope inherits a significant amount of ICS functionality from HPF, reusing the entire backend messaging system, and large portions of the subsystem protocols and frontends. We will describe this extension of the ICS, and the potential for use in other astronomical instruments.

9913-75, Session PS3

Development of a real-time data processing system for a prototype of the Tomo-e Gozen wide field CMOS camera

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The Universe is full of transient events, such as novae and supernovae. Such rare and energetic events drive the chemical evolution of galaxies. Time-domain astronomy aims to understand the transients in the Universe. It is difficult to predict the loci of the transients. A wide-field camera is

required to detect the transients events. The Tomo-e Gozen is an extremely wide-field optical camera, equipped with 84 CMOS sensors. The Tomo-e Gozen, installed in the Kiso 105-cm Schmidt telescope, will cover about a 20 sq-degree area, continuously recording universe at 2 Hz. The Tomo-e Gozen will be one of the most powerful instruments to investigate the sub-second Universe, such as an optical counter part of fast radio bursts, meteors, and near-earth objects. We have developed a prototype of the Tomo-e Gozen (Tomo-e PM), which has 8 CMOS sensors aligned in the RA direction, to evaluate the basic design of the Tomo-e Gozen.

The CMOS sensor equipped by the Tomo-e PM has about 2.2M pixels. A single exposure by the Tomo-e PM produces data as much as 35MB. The Tomo-e PM can obtain images continuously at 2 Hz. The data rate of the Tomo-e PM is about 70 MB/s and about 250 GB data are generated in an hour. We have developed an operating system to handle a large amount of data generated by the Tomo-e PM. The Tomo-e PM is operated by two PCs. Each of them retrieves data from four CMOS sensors. The data are converted into fits images and immediately sent to another PC for a storage. The operating system is successfully installed in the Kiso observatory and all the operations can be executed in a remote connection.

Fast transient events (fast radio burst counterparts) and fast moving objects (meteors) are main targets of the Tomo-e PM. Such objects appear only in a handful of images among the data generated by the Tomo-e. We have been developing softwares to detect such a rare event in a tons of data. Since the data are continuously generated, the data reduction should be as fast as the data production by the Tomo-e PM. Parallel computation, eliminating time-consuming tasks, and reducing IO overhead are key technologies. The Tomo-e Gozen camera with 84 sensors will generate about 10-times as much data as the Tomo-e PM does, corresponding to 30 TB/night. It is not realistic to store all the data generated by the Tomo-e Gozen. An on-site data reduction system and fast signal detection algorithms are crucial to make the best use of the Tomo-e Gozen.

9913-80, Session PS3

Introduction to measurement and control system of FAST active reflector

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Five-hundred-meter Aperture Spherical radio Telescope (FAST) will be the largest single dish radio telescope in the world which is under construction in Guizhou province in China. Being different from traditional telescopes, FAST's active main reflector is deformable and composed of over 4400 triangular panels. While the telescope is observing, panels transform into corresponding paraboloids which apertures are 300 meters. In order to achieve the reflector's active deformation, we have reflector measurement system and reflector control system to track and control the whole reflector with high precision and high efficiency.

The active main reflector has a cable mesh composed of ~7000 strands of steel cables. Over 4400 triangular panels are mounted on it. Thus there are 2225 nodes in the cable net and 2225 down-tied cables connecting nodes to the ground. The actuators are installed at the end of down-tie cables so that they can adjust the positions of the nodes and shape the reflector through stress deformation of the cable mesh.

The reflector measurement system mainly consists of 10 total stations as survey stations, 2225 targets which are installed on all the nodes, 24 foundation piers as differential reference stations and two control servers. The measurement precision requirement in calibration mode is RMS 1.5mm, in observing mode is RMS 2mm. The measurement efficiency requirement in calibration mode is measuring the whole reflector in 1.5 hour, in observing mode is measuring the corresponding paraboloid in 10 minutes.

The aim of reflector control system is to shape the precise paraboloid by controlling the 2225 actuators according to observation trajectory planning and measurement data. All the 2225 nodes are divided into 12 control areas. Each area has a relay station to communicate with master control room through double-ring fiber Ethernet. The master control room receives data and alarm information from PLCs at 12 relay stations. Meanwhile, it sends data to PLCs, including control instructions, time synchronization information, nodes' measurement information, etc. At the local control layer, PLCs receive the data from sensors installed on the actuators and send target location information to the actuators.

This paper will introduce the measurement system and control system of FAST active reflector respectively. In the measurement system part, we will introduce the system's overall design, working process, software detailed design and implementation. In the control system part, we will focus on its overall design, working process, hardware detailed design and implementation.

9913-84, Session PS3

A reorganization cyber infrastructure of history observing data in China

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Astronomical data analysis depends on the accumulation of data, including integrity of data in observing location, time, and diversity of data. We are now developing a reorganization project of solar physics history data of China. There are 90 years, 44 kinds of solar observing data in china. In the project, we will finish imagination, digitalization and standardization for these data. This article introduces the project framework, data, data processing, and how to share.

9913-88, Session PS3

The survey operation software system development for prime focus spectrograph on Subaru Telescope

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The Prime Focus Spectrograph (PFS) is a wide field multi-fiber spectrograph using the prime focus of the Subaru telescope, with capable of observing up to 2400 astronomical objects containing ~200 calibration targets.

Entire software system is designed as loosely coupled system, and is categorized into four packages. The instrument control system will execute the observation procedure communicating with hardware control subsystems and also will run in collaboration with the sequencing system for entire the Subaru telescope. The exposure targeting software calculates assignments of target objects to fibers and their positions for each exposure with various deformations and displacements caused by optics and observational conditions in consideration such as atmospheric dispersion, residual of its correction by ADC, and deformations of the prime focus instrument. The data reduction pipeline will reduce acquired data to spectroscopic parameters, and also will be used for on-site exposure quality assurance mainly using calibration stars.

The survey planning and tracking software is for managing entire survey plans and tracking their progress, based on the field tiling definition supplied from science survey operators. This package will coordinate efficient assignment of target objects to multiple exposures for each tile, and also will track progress of the entire survey to update sequences and configurations of planned exposures.

Based on loosely coupled system, these packages are consisted with functional modules and sequences. Functional system sequences provided from each package, such as exposure by the instrument, calibration, or map list of targets to fibers, will be used by operators of observations and survey, or users to do their science with PFS, and are built with calling selected modules providing functionality in need from both within and external packages to complete each purpose. These external interfaces provided from modules will be modeled over standardized data model, and could be switchable depends on targets.

Subsystem modules of the instrument control software will be mostly connected each other and called from sequences through the messaging hub server, which we selected the tron system used for SDSS, and its sequencer is also built as a module connected to the server. Some modules from other PFS software packages will be called from this sequencer locally, but not adding wrappers to these modules to the server.

In the survey planning and tracking software and the data reduction pipeline, sequencers will call required subsystem modules or other packages locally or through framework for parallel computing.

To carry out survey operations efficiently, information necessary to proceed survey, such as properties of target objects from imaging surveys, or survey coordination including exposure configurations, will be stored in database system shared among software packages.

These database system will be located at multiple places depends on its purpose, especially for observation execution, its database need to be at the site of observation for secure operation to deal with sudden disconnection from external.

Flows of data between these databases will be studied following development of the software packages and their data models.

9913-92, Session PS3

Status of the array control and data acquisition system for the Cherenkov Telescope Array

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The Cherenkov Telescope Array (CTA) will be the next-generation ground-based observatory using the atmospheric Cherenkov technique. The CTA instrument will allow researchers to explore the gamma-ray sky in the energy range from 20 GeV to 300 TeV. CTA will comprise two arrays of telescopes, one with about 100 telescopes in the Southern hemisphere and another smaller array of telescopes in the North. CTA poses novel challenges in the field of ground-based Cherenkov astronomy, due to the demands of operating an observatory composed of a large and distributed system with the needed robustness and reliability that characterize an observatory.

The array control and data acquisition system of CTA (ACTL) provides the means to control, readout and monitor the telescopes and equipment of the CTA arrays. The ACTL system must be flexible and reliable enough to permit the simultaneous and automatic control of multiple sub-arrays of telescopes with a minimum effort of the personnel on-site. In addition, the system must be able to react to external factors such as changing weather conditions and loss of telescopes and, on short timescales, to incoming scientific alerts from time-critical transient phenomena. The ACTL system provides the means to time-stamp, readout, filter and store the scientific data at aggregated rates of a few GB/s. Monitoring information from tens of thousands of hardware elements need to be channeled to high performance database systems and will be used to identify potential problems in the instrumentation. This contribution provides an overview of the ACTL system and a status report of the ACTL project within CTA. (For the CTA Consortium)

9913-96, Session PS3

ODI-PPA: 2016 project updates related to upgraded 5x6 ODI instrument

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The One Degree Imager – Portal, Pipeline, and Archive (ODI-PPA), a web science gateway providing astronomers a single point of access to ODI data as well as rich computational and visualization capabilities, has been in operation since early 2012. Related to the significant upgrade of the ODI instrument focal plane to a 5x6 array (from a 3x3 array) of Orthogonal Transfer Arrays (OTAs), we made several improvements to ODI-PPA to elegantly handle the larger data sizes and the associated changes in expectations from the WIYN Operational and the ODI user perspective. While 3x3 pODI's data volumes were significant enough to deter downloading and processing of raw data into calibrated science data and stacks, the 5x6 data volumes are roughly 3 times the size of pODI data so it became even more important for us to provide rock-solid calibration and stacking functionality within PPA. We improved the QuickReduce workflow within PPA to allow use of twilight flats or custom calibration images (instead of using operator produced monthly master calibrations), as well as more extensive customization of the corrections applied to each input raw image. We also integrated the SWarp stacking pipeline, and verified it works with the larger 5x6 ODI images. This cloud-based stacking can be used with any stacking pipeline, and adds significantly to the overall usefulness of the archive, as a) essentially all

ODI data is obtained using dithering, with the total exposure time being spread out over several shorter exposure spatially offset from each other; b) generating stacks of even a single, typically 9-point, dither sequence requires significant computational resources and large amounts of disk space for both input and intermediate data files (>20 GB for a single sequence, 250+ GB for deeper observations or wider fields). Co-locating data storage (archive) and processing (portal) therefore enables users from the general astro-community to get the most out of their data while minimizing data transfers and local computing demands. We maintain data provenance for stacks produced within PPA in a manner similar to QuickReduce images and their association with raw images (which are now more comprehensive). Apart from the above improvements we also made several other user interface enhancements including: a uniform job status monitoring view for all Tier 2 workflows including QuickReduce and SWarp leveraging the Trident SCA Progress microservice, an improved Image Explorer functionality via the Trident SCA Image X microservice, and improved heuristic searches providing 'best available data' for any selection criteria while separating operator produced and user-derived data products (especially useful for novice users). Other updates include improved scaling for QuickReduce image tiles used by the ImageX visualization feature, the ability to seamlessly acquire compute nodes as needed to match processing demands, and operational stability enhancements providing better monitoring of underlying backend services.

9913-100, Session PS3

The TESS science processing operations center

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The Transiting Exoplanet Survey Satellite (TESS) was selected by NASA's Explorer Program to conduct a search for Earth's closest cousins starting in late 2017. Tess will conduct an all-sky transit survey of F, G and K dwarf stars between 4 and 12 magnitudes and M dwarf stars within 200 light years. TESS is expected to discover ~1,000 small planets less than 4X the size of Earth, and to measure the masses of at least 50 of these small worlds. Because these stars are typically 10X closer and 100X brighter than the Kepler's, they are much more amenable to follow-up observations and characterization. Indeed, the James Webb Space Telescope should be able to characterize the atmospheres of many of the TESS discoveries.

The TESS science pipeline is being developed by the Science Processing Operations Center (SPOC) at NASA Ames Research Center based on the highly successful Kepler pipeline. Like the Kepler pipeline, the TESS pipeline will provide calibrated pixels, simple and systematic error-corrected aperture photometry, and centroid locations for all 200,000+ target stars, observed over the 2-year mission, along with associated uncertainties. The science data will be processed on the NAS Pleiades Supercomputer for efficiency. The pixel and light curve products are modeled on the Kepler archive products and will be archived to the Mikulski Archive for Space Telescopes (MAST). In addition to the nominal science data, the 30-minute Full Frame Images (FFIs) simultaneously collected by TESS will also be calibrated by the SPOC and archived at MAST.

Each 27.4-day period, TESS will observe a 24° by 96° swath of sky extending from ~6° above ecliptic equator to the ecliptic pole in the anti-Sun direction. TESS rotates by 27.7° after each observing "sector" in order to cover one hemisphere during the first year of observations. The spacecraft then flips over to cover the other hemisphere during the second year. While most of the stars are only observed for 27.4 days, the "pole" camera is centered on the celestial pole, allowing a ~450 square degree area in each hemisphere to be observed continuously for a year.

The TESS pipeline will search through all light curves for evidence of transits that occur when a planet crosses the disk of its host star. The Data Validation pipeline will generate a suite of diagnostic metrics for each transit-like signature discovered, and extract planetary parameters by fitting a limb-darkened transit model to each potential planetary signature. The results of the transit search will be modeled on the Kepler transit search products (tabulated numerical results, time series products, and pdf reports) all of which will be archived to MAST.

This paper provides an overview of the TESS science pipeline and describes the development of the SPOC remaining before launch in August 2017. The data rate for TESS is 10X that of Kepler, presenting challenges for keeping up with the 27-day cadence of observations for a mission with 26 distinct fields of view. We describe innovations allowing us to scale the Kepler design to meet TESS's demanding requirements.

9913-104, Session PS3

The Infrared Imaging Spectrograph (IRIS) for TMT: software design

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IRIS (InfraRed Imaging Spectrograph) is a first light near-infrared diffraction-limited imager and integral field spectrograph being designed for the future Thirty Meter Telescope (TMT). We present the preliminary software design for the instrument, which features on-instrument wavefront sensors, an imaging focal plane consisting of four infrared detectors, and an integral field spectrograph with both lenslet array and mirror slicing IFUs. Challenging aspects of the software design include a real-time and offline data reduction system, the use of on-detector guide windowing to provide tip/tilt information to the AO system, and the approach to detector exposure data gathering that consists of continuously clocking the detector and storing all non-destructive reads. The system is part of the TMT Observatory Software system and will make use of TMT Common Software for its services.

9913-69, Session PS4

Software design of the ASTRI camera server proposed for the Cherenkov Telescope Array

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The Italian National Institute for Astrophysics (INAF) is leading the ASTRI project within the ambitious Cherenkov Telescope Array, CTA. In the framework of the small size class of telescopes, a first goal of the ASTRI project is the realization of the end-to-end prototype in dual-mirror configuration (SST-2M) with the camera at the focal plane composed by a matrix of Silicon photo-multiplier sensors managed by innovative front-end and back-end electronics. The ASTRI SST-2M prototype is installed in Italy at the INAF "M.G. Fracastoro" observing station located at Serra La Nave, 1735 m a.s.l. on Mount Etna, Sicily. As a second step, the ASTRI project is focussed on the implementation of the ASTRI mini-array composed of nine SST-2M telescopes and proposed to be placed at the CTA southern site.

This paper outlines the design of the camera server software that will be installed on the ASTRI mini-array. The software is based on the version installed on the ASTRI SST-2M prototype operating in a single telescope configuration. The migration from the single telescope to the mini-array context has required additional interfaces in order to guarantee high interoperability with other software and hardware components. In the mini-array configuration each camera communicates with the relevant camera server via a dedicated high rate data link. The primary goal of the camera server is to acquire the bulk data, packet by packet, without any data loss and to timestamp with each packet very precisely.

During array operation, the camera server receives from the SoftWare Array Trigger (SWAT) the list of science events that participate in a stereo triggered events. These events, and all the other events that are flagged either by the Camera as interleaved calibration or by the camera server as possible single-muon events, are sent to the Array DAQ. All remaining events will be discarded.

A suitable buffer is provided to perform this processing on all the incoming event packets. The camera server provides interfaces to the array control software to allow for monitoring and control during array operations.

In this paper we present the design of the camera server software with particular emphasis on the external interfaces. In addition we report the results of the first integration activities and performance tests.

9913-73, Session PS4

From source control to continuous delivery through integration and testing: a story of software automation

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Software projects are often approached with enthusiasm and they are easily managed during their early life stages, when developers are fully committed to the new product, but as a software project grows in size and complexity its lifecycle needs to be managed with increasingly powerful and standardized tools and practices, in order to keep its releases stable, tested and deployable in predictable times. This was also the case for DISCOS, the "Development of the Italian Single-dish COntrol System": a software project born for the control of the newly-built SRT radiotelescope and now extended to be used at all the Italian dishes.

If a version control system was essentially enough for managing the first stages of the project, when our codebase grew over 500,000 lines of code - encompassing different tags and different configurations installed at different telescopes - the old naive approach began to face its limits. For this reason we are gradually evolving our software management infrastructure and our software development process, with the goal of a complete continuous delivery.

In this paper we examine the shortcomings of the less structured approach and its impact on the development activity. We show how we are addressing the continuous integration and software management automation, with a particular focus on the lessons learned in introducing these techniques during a late stage of a project life. We illustrate how this impacted on the project itself in terms of how the code was developed and structured, and in terms of how the deployment operations were performed by our DevOps staff, analyzing the difficulties we encountered and the necessary tradeoffs we had to accept.

We describe how we automated the machine provisioning with the usage of virtual machines and containers, based on Vagrant, VirtualBox and docker, and how we automated the build jobs, using Jenkins for integrating our build process with our version control system. We show how we modified our project in order to make space for unit testing and functional testing in Python and C++, using Google Tests and the python unittest module, then adding automated testing duties to our build server giving access to new practices such as acceptance testing and implementation of regression tests. All these improvements can now be exploited during the deployment operations, using automated provisioning and binary artifacts of production and development releases of DISCOS for obtaining a repeatable and predictable deployment process in a safer environment.

In conclusion we examine the status of this transition towards a more modern software management process, discussing the future steps towards continuous delivery, showing how developing such an infrastructure is worth the initial effort and why it is going to pay off in the long run in terms of productivity and stability of the released software products.

9913-77, Session PS4

ZeroC ICE distributed middleware in the Tian Ma Telescope observing control system

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The Tian Ma Telescope (TM) is the largest fully steerable radio telescope in China. It has a primary reflector of 65-m in diameter with a shaped Cassegrain configuration. It operates in a wide frequency range from 1.4 GHz to 43 GHz.

There are many challenges controlling the TM and one of them is establishing reliable and robust communications between different parts of the telescope such as antenna, active surface, backend and so on. We selected Zeroc ICE middleware as a communication foundation to support control and status query. Now the observing control system based on the middleware works well. In this paper we discuss advantages of the ZeroC ICE middleware and implementation details of the observing control system.

9913-81, Session PS4

SINBAD flight software: the on-board software of NOMAD in Exomars 2016

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The Nadir and Occultation for MArs Discovery instrument (NOMAD), in mission ExoMars Trace Gas Orbiter (TGO), has as goal looking for trace gases that could be signatures of active biological or geological processes in Mars. This instrument is a spectrometer suite that consists of three separate channels, solar occultation (SO), limb nadir and occultation (LNO), and ultraviolet and visible spectrometer (UVIS).

The Spacecraft INterface and control Board for NomAD (SINBAD) is the electronic interface in charge of managing the power and communication inside NOMAD.

The SINBAD Flight Software (SFS) is the flight software embedded in SINBAD. It main tasks have been defined as follows.

Manage the communication interfaces with TGO spacecraft. These interfaces are implemented by a MIL-STD-1553B bus for telecommands (TCs) and housekeeping (HK) transmissions and a Spacewire bus for massive data transmission.

Control the observation sequence of NOMAD channels (SO, LNO and UVIS). When a telecommand with an observation is received, SFS sends the appropriate set of parameters to the channels and afterwards it reads the data produced. These data are transmitted later to the spacecraft.

Manage code and data patches. These patches can be implemented with file system operation or directly accessing to the system memory.

Implement the NOMAD contingency and recovery plan to detect and recover the instrument until the next communication with ground.

Control other devices of NOMAD such as: the LNO flip mirror, current and temperature sensors and operational heaters.

The ExoMars TGO mission has hard restrictions in number of TCs (750 every 5 days) and size (64 B per TC). All the communications with NOMAD (command observations, send patches, warn of powering off, etc...) should be done through TCs and some of them need a great number of TCs. In order to reduce the number of required TCs for nominal operations, such as observations, SINBAD stores the observation parameters in the on board memory in Channel Observation Parameters (COP) tables. With these structures, one single TC is needed to command a complete observation.

SINBAD uses a Non-Volatile magneto resistive random access memory (MRAM). It is the first time that this kind of memory is used as main memory in a flight mission.

This paper includes a summary of the most remarkable aspects about the SFS design and a description of the main problems and lessons learned during the software development.

9913-85, Session PS4

Porting the ALMA correlator data processor from hard real-time to plain Linux

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The ALMA correlator back-end consists of a cluster of 16 computing nodes and a master collector/packager node. The mission of the cluster is to process time domain lags into auto-correlations and complex visibilities, integrate them for some configurable amount of time and package them into a workable data product. Computers in the cluster are organized such that individual workloads per node are kept within achievable levels for different observing modes and antennas in the array. During the course of an observation the master node transmits enough state information to each involved computing node to specify exactly how to process each set of lags received from the correlator. For that distributed mechanism to work, it is necessary to unequivocally identify each individual lag set arriving at each computing node. The original approach was based on a custom hardware interface to each node in the cluster plus a real-time version of the Linux Operating System. A modification recently introduced in the ALMA correlator consists of tagging each lag set with a time stamp before delivering them to the cluster. The time stamp identifies a precise 16-millisecond window during which that specific data set was streamed to the computing cluster. From the time stamp value a node is able to identify a centroid (in absolute time units), base-lines, and correlator mode during that hardware integration. That is, enough information to let the digital signal processing pipeline in each node to process time domain lags into frequency domain auto-correlations per antenna and visibilities per base-line. The scheme also means that a good degree of concurrency can be achieved in each node by having individual CPU cores process individual lag sets at the same time, thus rendering enough processing power to cope with a maximum 1 GB/sec output from the correlator. The present paper describes how we time stamp lag sets within the correlator hardware, the implications to their on-line processing in software and the benefits that this extension has brought in terms of software maintainability and overall system simplifications.

9913-89, Session PS4

Implementing the concurrent operation of sub-arrays in the ALMA correlator

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The ALMA correlator processes the digitized signals from 64 individual antennas to produce a grand total of 2016 correlated base-lines, with runtime selectable lags resolution and integration time. The on-line software system can process a maximum of 125M visibilities per second and producing an archiving data rate close to one sixteenth of the former (7.8M visibilities per second with a network transfer limit of 60 MB/sec). Mechanisms in the correlator hardware design make it possible to split the total number of antennas in the array in smaller subsets, or sub-arrays, such that they can share correlator resources while executing independent observations. The software part of the sub-system is responsible for configuring and scheduling correlator resources in such a way that observations among independent sub-arrays occur simultaneously while internally sharing correlator resources under a cooperative arrangement. Configuration of correlator modes through its CAN-bus interface and periodic geometric delay updates are the most relevant activities to schedule concurrently while observations happen at the same time among a number of sub-arrays. For that to work correctly the software

interface to sub-arrays schedules shared correlator resources sequentially before observations actually start on each sub-array. Start times for specific observations are optimized and reported back to the higher level observing software. After that initial sequential phase has taken place then simultaneous executions and recording of correlated data across different sub-arrays move forward concurrently, sharing the local network to broadcast results to other software sub-systems. The present paper presents an overview of the different hardware and software actors within the correlator sub-system that implement some degree of concurrency and synchronization needed for seamless and simultaneous operation of multiple sub-arrays, limitations stemming from the resource-sharing nature of the correlator, limitations intrinsic to the digital technology available in the correlator hardware, and milestones so far reached by this new ALMA feature.

9913-93, Session PS4

The ASTRI mini-array software system (MASS) implementation: a proposal for the Cherenkov Telescope Array

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The ASTRI mini-array, composed of nine small-size dual-mirror (SST-2M) telescopes, has been proposed to be installed at the southern site of the Cherenkov Telescope Array (CTA), as a set of pre-production units of the CTA observatory. The ASTRI mini-array is a collaborative effort led by the National Institute of Astrophysics INAF (Italy) in partnership with the University of Sao Paulo and FAPESP (Brazil) and the North-West University (South-Africa). We present the main features of the current implementation of the Mini-Array Software System (MASS) now in use for the activities of the ASTRI dual-mirror small-size telescope prototype located at the INAF observing station on Mt. Etna, Italy and the characteristics that make it a prototype for the CTA control software system. CTA Data Management (CTA-DATA) and CTA Data Acquisition and Array Control (CTA-ACTL) requirements and guidelines as well as the ASTRI use cases were considered in the MASS design, most of its features are derived from the Atacama Large Millimeter/sub-millimeter Array Control software. The MASS will provide a set of tools to manage all on-site operations of the ASTRI mini-array in order to perform the observations specified in the short-term schedule (including monitoring and controlling all the hardware components of each telescope and calibration devices), to analyze the acquired data online and to store/retrieve all the data products to/from the on-site repository.

9913-97, Session PS4

Concept study of an observation preparation tool for MICADO

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MICADO, the near-infrared Multi-AO Imaging Camera for Deep Observations, will be one of the first light instruments for the European Extremely Large Telescope (E-ELT) of the European Southern Observatory (ESO). It is currently being developed by a consortium of German, French, Austrian, Dutch, and Italian institutes. Optimized to work with the laser guide star multi-conjugate adaptive optics facility MAORY and additionally equipped with a single-conjugated adaptive optics (SCAO) module for operation in a stand-alone mode, MICADO will provide capabilities for astrometric imaging, coronagraphic imaging, and spectroscopy over a large wavelength range at moderate resolution.

As for any other instrument in operation at an ESO observatory, observations with MICADO will have to be prepared in advance. Assuming a similar data flow as for, e.g., the Very Large Telescope (VLT), this will be accomplished by means of a combination of both standard and instrument-specific software tools. In this way the preparation overhead at the telescope can be restricted to a minimum, as well as the particular requirements on the instrument configuration, including plausibility tests and optimizations, can be covered through a custom implementation.

In case of MICADO the observation preparation particularly includes the automatic or manual selection of suitable natural guide stars for adaptive optics as well as of several reference stars for the envisaged secondary guiding through consecutive readouts of small MICADO detector windows. Together with the definition of an offset and dither pattern that is compliant with the selected asterism and depending on the actual AO and observation modes, this is a task which cannot be performed by standard software alone and that requires an optimization for the best possible configuration. In addition, a visual representation of the latter, along with both a dedicated graphical and a scripting interface, would be highly desirable. Finally and as a further option, the MICADO instrument simulator, to be provided by the consortium independently, might eventually be integrated. Therefore, we aim at the development of a flexible, user-friendly, and expandable tool that fulfills the aforementioned requirements and that either enhances or complements the ESO standard observation preparation software.

In the Preliminary Design Phase of the MICADO project we are currently examining different application type options ranging from plug-ins to

stand-alone tools, and we are investigating how the requirements can be reflected in a feasible software design through the prototyping of selected functionalities. We report on the status of our conceptual design study and present a first proof-of-concept implementation of an observation preparation tool for MICADO.

9913-101, Session PS4

Implementation of a distributed system for the PAUCam control system

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The PAU Camera is an instrument equipped with 18 red-sensitive CCDs of 4kx2k pixels with a system of 40 narrow-band (10 nm) filters and 6 wide-band filters which is installed as a visitor instrument at the William Herschel Telescope(WHT).

The PAUCam Camera Control System (CCS) is the software system in charge of the coordination of the several subsystems of PAUCam to acquire exposures, monitor the whole system, check and configure the system and process lists of targets.

The PAUCam CCS is based on a central node (Observation Control System, OCS) and several satellites. The satellites implement interfaces to subsystems of PAUCam or the telescope, while the OCS is in charge of their coordination to execute tasks. The list of satellites includes: Slow Control interface, Data Acquisition interface, On line Quality analysis, Guider, Telescope Control system interface, Storage and Transfer, and buffer.

The PAUCam CCS is a distributed software system which uses "Advanced Messaging Queue Protocol"(AMQP) to implement the communication system. A Shared Variable Engine has been developed on top of AMQP, allowing satellites to share variables in real time. The OCS, by means of Remote Procedure Calls (RPC), sends requests to satellites which are executed on a sandbox environment. OCS also implements the concept of macros which let add functionality to the system easily.

PAUCam can be operated either in manual or in supervised mode. On supervised mode a list of targets are processed sequentially, while in manual mode, the operator has to set each of the tasks to be performed.

9913-105, Session PS4

A 1D spectral extraction software with self learning capabilities for the FOCES spectrograph

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We described a new generation of spectral extraction and analysis software package for the Fibre Optics Cassegrain Echelle Spectrograph (FOCES), which will be attached to the 2-m Fraunhofer Telescope on the Wendelstein Observatory. The package includes a variety of image processing algorithms based on Python language and third party, open source packages Numpy and Scipy. An optimal extraction method was adopted to obtain the one-dimensional spectra with cosmic rays removed. The radial velocities of the multi-order echelle spectra were calculated by minimizing the ?2 with the templates, which were generated either by combining the observed high signal-to-noise spectra, or the synthesis program of the MAFAGS-OS model atmosphere. The package was also optimized for the laser frequency comb, which was used as the wavelength reference to obtain the radial velocity uncertainties down to sub-m/s.

9913-108, Session PS4

Monitoring service for the Gran Telescopio Canarias control system (GCS)

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Background

Grantecan is a 10.4 meter Telescope. Grantecan Control System follows a distributed architecture in three tiers, namely equipment real-time control, common services and user interfaces.

The equipment real-time control tier is composed of several embedded systems that connect to the hardware in order to command and to read the telemetry information. These Logical Control Units make use of the common service located in the second tier.

Within the intermediate layer, that aggregates services like: configuration, alarms, logging and so on, it is located the Monitor Manager service, in charge of data collecting, distribution, processing and storage of Telescope and Instruments telemetry. This service decouples real-time streams coming from different subsystems and allow users (Astronomers and Operators) to analyse data at its their own pace while archiving historical data so its availability and performance is key for overall Telescope performance.

Due to several limitations of the former GTC Monitor Manager, a new designed version has been developed and placed in operation recently. This paper presents the innovative design of the new service, which includes more demanding requirements in terms of high availability and fault tolerance, enhanced performance and further scalability for present and future instruments. Latest state-of-art technologies in real time database within distributed system, no single point of failure, easy of integration and maintenance have been among the requisites considered and applied.

Results

Several strategies were adopted, like building a robust set of queues based on Terracota memory management tools, that distributes and buffer telemetry data in parallel streams which can be replicated to achieve scalability at the time that overcome data loss due to unavailability of certain devices. Monitor Manager server was then completely isolated from the Real-Time tier using these queues and a product/consumer architecture which separate producers and consumers data paths. High availability solution was developed based on memory storage shared by different processes and synchronization among them, becoming a cluster with no single point of failure, that provides short term telemetry to user presentation layer. Finally, as a special consumer, a classic MySQL Master Multi-Slave database architecture was selected to provide a Long Term data archive and to facilitate the offline analysis of the data.

Conclusion

This paper presents the architecture of the new GTC System Monitoring, the technical tradeoff taken during design phase, and the alternative paths that were evaluated during its development.

9913-111, Session PS4

ESPRESSO front end guiding algorithms: from design phase to implementation and validation toward the commissioning

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In this paper we will review the ESPRESSO guiding algorithm for the Front End subsystem. ESPRESSO, the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations, will be installed on ESO's Very Large Telescope (VLT). The Front End Unit (FEU) is the ESPRESSO subsystem which collects the light coming from the Coud`e Trains of all the Four Telescope Units (UTs), provides Field and Pupil stabilization better than 0.05'' via piezoelectric tip tilt devices and inject the beams into the Spectrograph fibers. The field and pupil stabilization is obtained through a re-imaging system that collects the halo of the light out of the Injection Fiber and the image of the telescope pupil. In particular, we will focus on the software design of the system starting from class diagram to actual implementation. A review of the theoretical mathematical background required to understand the process of simulations needed to achieve the final design is also reported. We will show the performance of the designed algorithm on the actual Front End by adoption of telescope simulator exploring various scientific requirements.

9913-114, Session PS4

HIRES the high resolution spectrograph for the E-ELT: software and hardware solutions for its control

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The current E-ELT instrumentation plan foresees a High Resolution Spectrograph conventionally indicated as HiRes whose Phase A study will start in 2016. Since 2013 however, a preliminary study of a modular E-ELT instrument able to provide high-resolution spectroscopy (R~100,000) in a wide wavelength range (0.37-2.5 ?m) has been already conducted by an international consortium (termed "HiRes initiative"). Taking into account the requirements inferred from this preliminary work in terms of both high-level operations as well as low-level control, we will present in this paper possible solutions for HiRes hardware and software architecture. The validity of the proposed architectural and hardware choices will be eventually discussed based also on the experience gained on a real-working instrument, ESPRESSO, the next generation high-stability spectrograph for the VLT and to certain extent the precursor of HiRes.

9913-117, Session PS4

Monitoring and controlling the SKA telescope manager: a peculiar LMC system in the framework of the SKA LMCs

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The SKA Telescope Manager (TM) is the core package of the SKA Telescope: it is aimed at scheduling observations, controlling their execution, monitoring the telescope health status, diagnosing and fixing its faults and so on. To do that, TM directly interfaces with the Local Monitoring and Control systems (LMCs) of the various SKA Elements (e.g. Dishes, Low-Frequency Aperture Array, etc.), exchanging commands and data with each of them.

TM in turn needs to be monitored and controlled, in order its continuous and proper operation – and therefore that of the whole SKA Telescope – is ensured. It appears indeed that, while the unavailability of one or more instances of any other SKA element should result only in a degraded operation for the whole telescope, a problem in TM could cause a complete stop of any operation.

In addition to this higher responsibility, a local monitoring and control system for TM has to collect and display logging data directly to operators, perform lifecycle management of TM applications and directly deal - when possible - with management of TM faults (which also includes a direct handling of TM status and performance data).

In this paper the peculiarities presented by the TM monitoring and control and the consequences they have on the design of a related LMC system are addressed and discussed.

9913-120, Session PS4

The software architecture of the camera for the ASTRI SST-2M prototype for the Cherenkov Telescope Array

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The purpose of this contribution is to present the current status of the software architecture of the ASTRI SST-2M Cherenkov Camera. The ASTRI SST-2M telescope is an end-to-end prototype for the Small Size Telescope of the Cherenkov Telescope Array. The ASTRI camera is an innovative instrument based on SiPM detectors and has several internal hardware components. In this contribution we will give a brief description of the hardware components of the camera of the ASTRI SST-2M prototype and of their interconnections. Then we will present the outcome of the software architectural design process that we carried out in order to identify the main structural components of the camera software system and the relationships between them. We will analyze the architectural model that describes how the camera software is organized as a set of communicating blocks. Finally, we will show where these blocks are deployed in the hardware components and how they interact. We will describe in some detail, the physical communication ports and external ancillary devices management, the high precision time-tag management, the fast data collection and the fast data exchange between different camera subsystems, and the interfacing with the external systems.

9913-129, Session PS4

INO340 telescope control system: middleware requirements, design, and evaluation

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The INO340 telescope is a 3.4m Alt-Az reflecting optical telescope with a 0.3° field-of-view and the F?ratio of Cassegrain focus is f/11. It is currently in the middle of the detailed design phase. The INO340 Control System (INOCS) is being designed in terms of a distributed real-time architecture comprised of many processors and devices. This system requires a communications layer that provides an efficient and reliable way of exchanging data between its different components. The real-time (soft and firm) nature of many processes inside INOCS causes the communication paradigm very critical and sensitive. Therefore, the middleware shall work at realtime to be able to satisfy INOCS functional and performance requirements.

INOCS high-level middleware is responsible for data transmission among INOCS main subsystems, i.e. the Observation Monitoring System (OMS), the Observation System Supervisor (OSS) and the Telescope Control System Supervisor (TCSS). The middleware must be adaptable to hardware infrastructure and operating system software that may differ between different nodes in INOCS. For this purpose, the Data Distribution Service (DDS) standard has been selected as the communications middleware to distribute information across the entire system. The DDS itself performs based on the well-known publish-subscribe paradigm.

There are several types of middleware and each has its own strong points. The point-to-point messaging type is built on the concept of message queues, senders, and receivers. The client-server model is a distributed application structure in computing that partitions tasks or workloads between the providers of a resource or service, called servers, and service requesters, called clients. The DDS standard is based on a publish-subscribe design pattern. Publish-subscribe applications are typically distributed applications with endpoint nodes that communicate with each other by sending (publishing) data and receiving (subscribing) data anonymously without knowing the destination address.

INOCS is a soft real-time system, therefore, its subsystems need to communicate fast with least possible data loss. After studying and evaluating several major DDS implementations, we have decided to use RTI DDS for INOCS data transmissions. Due to this decision, we shall first determine the feasibility of using RTI DDS as INOCS high level middleware and ensure that it meets our critical expectations and requirements. In order to evaluate RTI DDS, we have performed some analysis considering two important Quality of Service (QoS) factors: the Latency and Sample Loss using different CPU loads, to estimate the performance of INOCS middleware in ordinary and extreme circumstances.

In the first section of this paper we review, survey and compare the main middleware types which are mostly used in distributed real-time applications, and then we illustrate the middleware architecture of INO340 control system and handling the commands based on the use of the DDS standard. We have chosen this design pattern based on our system requirements in terms of functional, design, performance, architectural, operational, interface, reliability and maintainability which are completely discussed in the next section of the paper. These requirements could be served as the reference requirements to the design and evaluation of any middleware for future telescope control systems. In the last section, we present and discuss the different experimental results performed to evaluate the middleware implementation in INOCS based on publish-subscribe paradigm and DDS standards.

9913-132, Session PS4

ASTRI SST-2M data reduction and reconstruction software on low-power and parallel architectures

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In the framework of the Cherenkov Telescope Array (CTA) International observatory, the Italian National Institute for Astrophysics (INAF) is leading the “Astrofisica con Specchi a Tecnologia Replicante Italiana” (ASTRI) project devoted to the development of a next generation of small-sized dual-mirror (SST-2M) Imaging Atmospheric Cherenkov Telescopes (IACTs). A prototype of the ASTRI SST-2M telescopes has been installed in Italy at the INAF “M. G. Fracastoro” Astronomical Station located at Serra La Nave on Mount Etna, Sicily, and will be operational by the first half of 2016. A mini-array of nine ASTRI SST-2M telescopes has been proposed to be installed at the southern site of the CTA, as an initial seed of the entire observatory. The ASTRI mini-array is a collaborative effort led by INAF (Italy) in synergy with the University of Sao Paulo and FAPESP (Brazil) and the North-West University (South-Africa).

IACTs are typically located in isolated places in order to avoid luminous sky background. In such a remote site, the capability of each telescope to process its own data before sending them to a central acquisition system provides a key advantage: carrying out preliminary data reduction on the telescope would greatly decrease the bandwidth and power required by an array installation.

We implemented the complete analysis chain required by a single ASTRI SST-2M telescope on an NVIDIA Jetson TK1, a development board equipped with an heterogeneous NVIDIA Tegra System-on-Chip. Leveraging its efficient Kepler GPU and the four ARM cores, we show, on Monte Carlo simulation bases, that it can process twice as much of the required data flow (more than 2000 events/s) with a power consumption lower than 10 W. This makes Jetson TK1 a promising embedded processing module for the on-line data analysis of gamma-ray astronomy with Imaging Atmospheric Cherenkov Telescopes.

9913-135, Session PS4

Towards a dynamical scheduler for ALMA: a science-software collaboration

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State-of-the art astronomical facilities are costly to build and operate, hence it is essential that these facilities must be operated as much efficiently as possible, trying to maximize the scientific output and at the same time minimizing overhead times. Over the latest decades the scheduling problem has drawn attention of research because new facilities have been demonstrated that is unfeasible to try to schedule observations manually, due the complexity to satisfy the astronomical and instrumental constraints and the number of scientific proposals to be reviewed and

evaluated in near real-time. In addition, the dynamic nature of some constraints (i.e. the weather parameters and the uncertainty of completing an observation) makes this problem even more difficult.

The Atacama Large Millimeter/submillimeter Array (ALMA) is a major collaboration effort between European (ESO), North American (NRAO) and East Asian countries (NAOJ), under operations on the Chilean Chajnantor plateau, at 5.000 meters of altitude. Currently, it is the largest radio-telescope on Earth, it has 66 antennas of 12-meter and 7-meter diameter, distributed over a wide extension, with up to 16 kilometers of baseline separation. The ALMA interferometer will provide the possibility to be used as a single array, or as up to six minor independent logical arrays or groups of antennas. Over the observing season multiples arrays configurations could be available. This is achieved by moving the antennas from one predefined position to another. During normal operations at least two independent arrays are available, aiming to achieve different types of science. Since ALMA does not observe in the visible spectrum, observations are not limited to night time only, thus a 24/7 operation with little downtime as possible is expected when full operations state will have been reached. However, during preliminary operations (early-science) ALMA has been operated on tied schedules using around half of the whole day-time to conduct scientific observations.

The purpose of this paper is to explain how the observation scheduling and its optimization is done within ALMA, giving details about the problem complexity, its similarities and differences with traditional scheduling problems found in the literature. The paper delves into the current recommendation system implementation and the difficulties found during the road to its deployment in production.

9913-138, Session PS4

Software design and code generation for the engineering graphical user interface of the ASTRI SST-2M prototype for the Cherenkov Telescope Array

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ASTRI is an on-going project developed in the framework of the Cherenkov Telescope Array (CTA).

An end-to-end prototype of a dual-mirror small-size telescope (SST-2M) has been installed at the INAF observing station on Mt. Etna, Italy. The next step is the development of the ASTRI mini-array composed of nine ASTRI SST-2M telescopes proposed to be installed at the final CTA southern site. The ASTRI mini-array is a collaborative effort led by the National Institute of Astrophysics INAF (Italy) in partnership with the University of Sao Paulo and FAPESP (Brazil) and the North-West University (South-Africa).

To control the ASTRI telescopes, a specific ASTRI Mini-Array Software System (MASS) was designed using a scalable and distributed architecture to monitor all the hardware devices for the telescopes. MASS is built upon the ALMA Common Software (ACS) framework, which provide support in the implementation of monitoring and control of distributed systems, and uses the Open Platform Communication Unified Architecture (OPC-UA) protocol for the interface with the telescope components. MASS is being tested on the ASTRI SST-2M end-to-end prototype.

Using code generation we built automatically from the ASTRI Interface Control Documents a set of communication libraries and extensive Graphical User Interfaces that provide full access to the capabilities offered by the telescope hardware subsystems for testing and maintenance. Leveraging these generated libraries and components we then implemented a human designed, integrated, Engineering GUI for MASS to perform the verification of the whole prototype and test shared services such as the alarms, configurations, control systems, and scientific on-line outcomes.

9913-142, Session PS4

A friction observing and compensating method based on data fusing in telescope controller design

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In this paper, a friction identifier and compensator is proposed. Friction is a major disturbance of median or large volume telescope. But the dynamic friction can hardly be measured directly. This paper propose a method to observe the dynamic friction based on data fusing. And used the observed result to identify friction's parameters of LuGre model. A compensator based on these parameters is then designed to compensate the friction. Finally the experiment result is proposed.

9913-146, Session PS4

A real-time prediction system for solar weather based on magnetic nonpotentiality (I)

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The Sun is the source of space weather. The influence of the solar-terrestrial space environment on human life has become more and more direct. The characteristics and evolution of the solar active-region magnetic field closely relate to violent solar eruptions such as flares and coronal mass ejections. Vector magnetic-field observation is the observational basis of studying the physical properties of solar atmosphere and the theoretical models of solar activities. The Solar Magnetic Field Telescope in Huairou Solar Observing Station has accumulated numerous vector magnetogram data of solar photospheric active regions (AR) covering nearly 30 years. Utilizing these precious historical data to establish statistical prediction models for solar eruptive events, not only can provide a reference for the timely adjustment of observation mode to specific active regions, but also can offer valuable reference to the monitoring and forecasting departments of solar and space weather. In this part of work, we focus on the Yes/No and occurrence time predictions for AR-related solar flares, and the predictions independently rely on the vector magnetic-filed observation of the solar surface.

9913-148, Session PS4

Use cases to elicit the software requirements analysis within the ASTRI project

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The Italian National Institute for Astrophysics (INAF) is leading the Astrofisica con Specchi a Tecnologia Replicante Italiana (ASTRI) project aimed at the realization of a telescope for one of the small size class of telescopes (SST) for the Cherenkov Telescope Array (CTA). The first goal of the ASTRI project has been the development and operation of an innovative end-to-end telescope prototype using a dual-mirror optical configuration (SST-2M) equipped with a camera based on silicon photo-multipliers. The ASTRI SST-2M prototype has been installed in Italy at the INAF "M.G. Fracastoro" Astronomical Station located at Serra La Nave, on Mount Etna, Sicily. This prototype has been used to test several mechanical, optical, control hardware and software solutions which will be used in the ASTRI mini-array, comprising nine SST-2M telescopes to be placed at the CTA southern site. The ASTRI mini-array is a collaborative effort led by INAF in synergy with the University of Sao Paulo and FAPESP (Brazil) and the North-West University (South-Africa). We present here the use cases, through UML diagrams and text details, that describe the functional requirements of the software that will manage the ASTRI SST-2M prototype, and the lessons learned thanks to these activities. We intend to adopt the same approach for the Mini Array Software System (MASS) that will manage the ASTRI mini-array operations. Use cases are of importance for the whole software life cycle, in particular they provide valuable support to the validation and verification activities. Following the iterative development approach, which breaks down the software development into smaller chunks, we have analysed the requirements, developed and tested the code in repeated cycles. The use case technique allowed us to formalize the problem through user stories that describe how the actor procedurally interacts with the software system. Through the use cases we improved the communication among team members, fostered common agreement about system requirements, defined the normal and alternative course of events, understood better the business process, and defined the system test to ensure that the delivered software works properly.

We present a summary of the ASTRI SST-2M prototype use cases, and how the lesson learned can be exploited for the ASTRI mini-array proposed for the CTA Observatory.

9913-150, Session PS4

M&C Domain Map Maker: an environment complimenting MDE with M&C knowledge ensuring solution completeness

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The role of Model Driven Engineering (MDE) as a key driver to reduce development cost of M&C systems is beginning to find acceptance across scientific instruments such as ITER, SKA and other projects. Such projects are adopting it to reduce time to integrate, test and simulate their individual controllers and increase reusability and traceability in the process. Although there is significant tool support with MDE towards the creation of domain-models, there is still gap in the way the models are identified. We argue that the key factors influencing the definition of these models are knowledge about the M&C engineering lifecycle. This knowledge exists not just implicitly but also in silos in the minds of specialist such as M&C architects, engineers, commissioners, operators, maintainers and so on. This is evidenced by our previous works both carried out in the context of Square Kilometer Array (SKA): a) implementation of an integrated M&C design, testing and simulation framework b) development of a framework to capture the running state of the telescope to reason about the telescope status. Both work involved a collection of domain models specific to M&C design, testing and operations. The models supporting the design and testing were interconnected that allowed derivation of much of the input related to testing from the captured design. This reduced effort towards testing and simulation and also enhanced traceability between the design and testing phase. The runtime framework was implemented independently which too pointed towards the need for an integrated M&C domain model since the runtime view of the telescope needed to be in sync with its design view. This strongly indicated the need for an integrated M&C engineering domain model that enabled analysis and verification of the output created across all engineering phases. However, we saw a clear lack of process that enabled the creation of such an integrated domain model.

We feel that this can be done by linking MDE with problem domain knowledge. The complementary domain knowledge will ensure completeness and consistency in the defined domain-models and hence in the final solutions which the current MDE practice does not guarantee. This can be achieved through: a) explicating the domain knowledge b) using it as a basis to define the domain-models and their relations. Although there are environments that allow performing a and b independently, there is no process that connects the two. To mitigate this, we have come up with M&C Domain Map Maker, a set of processes and tools that enables explication of M&C domain knowledge in terms of domain models with mutual consistency relations. This paper discusses this approach.

9913-152, Session PS4

The RTE inversion on FPGA aboard the solar orbiter PHI instrument

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SO/PHI (Solar Orbiter Polarimetric and Helioseismic Imager) is a

filtergraph-based, solar magnetograph aimed at mapping the vector magnetic field and the line-of-sight (LOS) velocity of the solar photospheric plasma. It belongs to the scientific payload of the European Space Agency's Solar Orbiter mission which will orbit the Sun at 0.28 astronomical units.

The limited telemetry rate combined with the large amount of scientific information retrieved by the SO/PHI instrument demand a sophisticated on-board data reduction and scientific analysis through the study of the polarization state of a specific spectral line. The main aim is to perform the complicated algorithm needed to translate the polarization state of the light spectrum in terms of some specific solar parameters like the magnetic field vector and velocity. Technically speaking, the inference of the solar physical quantities through a spectropolarimetric study is based on the inversion of the Radiative Transfer Equation (RTE) and these tasks require the processing of a huge quantity of data in parallel.

The RTE inverter is the core of the on-board scientific data analysis and, probably, one of the most innovative parts of the instrument. Due to the unavailability of qualified for space processors, DSPs, or GPGPUs that fulfil the stringent computational requirements with the limited room and power consumption allocated to the instrument, a specifically designed hardware device has been implemented in SO/PHI. This device is in charge of inverting the RTE aboard Solar Orbiter under narrow time and power constraints.

The main aim of this work is to design, build, and test such a hardware device for SO/PHI. With that goal in mind, we propose a high-performance computing architecture for carrying out the RTE inversion using FPGA devices embedded in the SO/PHI instrument.

The computing proposal consists of a SIMD multiprocessor architecture to reach high performance in floating point operations. This architecture on a Virtex-4 FPGA squeezes the FPGA resources in order to reach the time constraints. It is focused in exploiting the data parallelism using several processors working together and using different data streams. One of the most important contributions of this architecture is the ability of saving resources allocating operation cores in a shared operation block, which is accessed by every processor. Some details for extending the architecture to other problems are pointed out.

Using the SIMD architecture, the challenge of carrying out the RTE inversion in less than 15 minutes has been reached. The architecture has not only demonstrated that is able to do it but it is also improves the computing capabilities of ground systems by more than ten times using a relatively slow (and 10 year-old) Virtex-4 FPGA device.

The RTE inverter prototype has been tested using real images taken by another instrument. It is able of working as accurately as usual computers regarding the scientific precision. In addition, it has satisfied the stringent requirements of power consumption and processing time.

9913-154, Session PS4

Knowledge-based engineering of a PLC controlled telescope

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As the new control system of the Mercator Telescope is being finalized, we can review some technologies and design methodologies that are advantageous, despite their relative uncommonness in astronomical instrumentation. Particular for the Mercator Telescope is that it is controlled by a single high-end soft-PLC (Programmable Logic Controller). Using off-the-shelf components only, our distributed embedded system controls all subsystems of the telescope such as the pneumatic primary mirror support, the hydrostatic bearing, the telescope axes, the dome, the safety system, and so on. We show how real-time application logic can be written conveniently in typical PLC languages (IEC 61131-3) and in C++ (to implement the pointing kernel) using the commercial TwinCAT 3 programming environment. This software processes the inputs and outputs of the distributed system in real-time via an observatory-wide EtherCAT network, which is synchronized with high precision to an IEEE 1588 (PTP, Precision Time Protocol) time reference clock. Taking full advantage of the ability of soft-PLCs to run both real-time and non real-time software, the same device also hosts the most important user interfaces (HMIs or Human Machine Interfaces) and communication servers (OPC UA for process data, FTP for XML configuration data, VNC for remote control, and HTTP for web-based interfaces). To manage the complexity of the system and to streamline the development process, we show how most of the software, electronics and systems engineering aspects of the control system have been modeled as a set of scripts written in a Domain Specific Language (DSL). When executed, these scripts populate a Knowledge Base (KB) which can be queried to retrieve specific information. By feeding the results of those queries to a template system, we were able to generate very detailed "browsable" web-based documentation about the system, but also PLC software code, Python client code, model verification reports, etc. The aim of this paper is to demonstrate the added value that technologies such as soft-PLCs and DSL-scripts and design methodologies such as knowledge-based engineering can bring to astronomical instrumentation.

9913-157, Session PS4

Aided generation of search interfaces to astronomical archives

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Astrophysical data provider organizations nearly always host web portals or web based interfaces providing public or restricted access to the data resources they manage.

Changes in the discovery logic, supported capabilities or data collections, results data formats or data access policies affect interface maintenance.

Each time one such change happens it could be necessary to rewrite search logic in the databases or modify the arrangement or elements of a web form, potentially on different web portals.

This takes time and is also error prone, so a standardized and reliable way to manage this issue was sought for.

It was thus decided to develop a dynamically configurable Java EE web application that can set itself up reading needed information from XML configuration files.

Specification of what information the astronomical archive database has to expose is managed using the TAP_SCHEMA schema from the IVOA TAP recommendation.

The TAP_SCHEMA lists which tables and columns are included in the service but also provides a way to store useful metadata like UCDs (Unified Content Descriptors), descriptions, units and so on.

To improve user experience and to allow tool usage also to people that don't have particular SQL skills a graphical interface has been developed that can be used to create or edit a TAP_SCHEMA instance.

This interface also includes a panel to perform search and validation of UCDs based on Strasbourg astronomical Data Center (CDS) dedicated services.

After setting up and populating the desired TAP_SCHEMA the user can specify what tables and columns should be involved in building the search query, how these elements have to be arranged in a form based web page and if the generated search interface should contain specific auxiliary elements like a text input to perform object name to position resolving, or explicit VO compliant output or other custom tool (e.g. a preview capability for datasets).

The configuration file will store also information about the database connection details, custom portal style elements (background images or

logos), and elements keeping track of which table fields store information concerning users accounts and web service logs.

The user of this tool, managing portal generation, will be able to do all of this directly editing the configuration file but it is also planned to code a wizard helper for generating this file in a graphical way.

When configuration steps are done the tool will build a war file to allow easy deployment of the application in (possibly different) web containers.

The XML configuration file can be saved for future editing and quick re-use.

9913-159, Session PS4

Single sign-on with Shibboleth in the MAST discovery portal

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The Mikulski Archive for Space Telescopes (MAST) is the official data archive for more than 15 missions, including HST, Kepler, GALEX, FUSE, IUE, EUVE, Swift and XMM. MAST's Discovery Portal is a rich web application for exploring data from all of those missions. The portal can also search and retrieve data from the Virtual Observatory (VO), thus provided one-stop access to a wide variety of other resources such as Spitzer, Chandra, 2MASS, WISE, Simbad and NED. By including search results for multiple missions, the Discovery Portal not only simplifies searching for known data, it facilitates the discovery of data previously unknown to the user.

Most of the MAST and VO data is public, so using the MAST Discovery Portal does not require a login. However, there are two main reasons why the Portal needs to provide a login capability. The first is that some data has access restrictions, such as HST and JWST data still within the proprietary period. Retrieval of such data must require both authentication and authorization of users. The second main purpose for user authentication is to allow search history and preferences to be saved for later use.

Shibboleth is a system that not only enables login to a single web page, but also provides single sign-on (SSO) capabilities for a set of protected web pages and services. That is, once a user logs into one of those web pages, the other pages and services can be accessed without logging in again. SSO will allow MAST Portal users to access other STScI services such as proposal preparation and grants management without needed to manage multiple accounts or logins.

In addition to managing users within an organization, Shibboleth can be configured to recognize users from other organizations. This federating of user identities is potentially a powerful feature for academic web sites such as the MAST Portal since Shibboleth is widely used by academic and scientific organizations.

While the SSO and user federation benefits are clear, Shibboleth is a challenging system to set up and manage. For example, it originally did not support sites that allowed anonymous access, so handling of those sites now is a bit clumsy. Another challenge lies in the complexity of the handshaking sequence required for user authentication. Web browsers hide much of this complexity from users and programmers alike, but when the service access is via Ajax calls from the browser, or from non-browser clients, the complexity cannot be escaped.

By relating our experiences in setting up SSO for the MAST Discovery Portal, we will illustrate several of the challenges facing both web developers and system administrators as they enable single-sign on for their organization.

9913-160, Session PS4

A control system framework for the Hobby-Eberly Telescope

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We present the development framework for the distributed control systems, scripting frontend, and monitoring facilities of the recently upgraded Hobby-Eberly Telescope (HET). A common flexible control and data acquisition layer in C++, with message passing implemented on top of ZeroMQ, wraps the final designs of each new hardware component including tracking, metrology, instrumentation and calibration equipment. A homogeneous command, response and event layer normalizes the diversity of the lower level software interfaces easing the development of the Telescope Control System (TCS). Applications developed in the framework easily interface to the new tracker and legacy instrumentation of the primary mirror, weather, dome, and tracker support structure. We demonstrate the framework's use in facilitating testing, vetting, and characterization of the telescope and TCS. Examples of the real-time monitoring capabilities and Python scripting methods of various telescope components are given. Lessons learned along the way, future refinements, and anticipated enhancements, are detailed.

9913-162, Session PS4

A user interface framework for the Square Kilometre Array: concepts and responsibilities

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The Square Kilometre Array (SKA) project is responsible for developing the SKA Observatory, the world's largest radio telescope, with eventually over a square kilometre (one million square metres) of collecting area and including a general headquarters as well as two radio telescopes, SKA1-Mid in South Africa and SKA1-Low in Australia. The SKA project consists of a number of subsystems (elements) among which the Telescope Manager (TM) is the one involved in controlling and monitoring the SKA telescopes.

The TM element has three primary responsibilities:

Management of astronomical observations;

Management of telescope hardware and software subsystems;

Management of data to support system operations and all stakeholders (operators, maintainers, engineers and science users) in achieving operational, maintenance and engineering goals.

Operators, maintainers, engineers and science users will interact with TM via proper user interfaces (UI).

The TM G/UI framework envisaged is a complete set of technical solutions (components, technologies and design information) for implementing a generic computing system (GUI platform). Such a system will enable G/UI components to be instantiated, allow for human interaction via screens, keyboards, mouse and implement the necessary logic for acquiring or deriving the information needed for interaction. It will provide libraries and specific Application Programming Interfaces (APIs) to implement operator and engineer interactive interfaces.

This paper will provide a status update of the TM G/UI framework, platform and components design effort, including the technology choices and discuss key challenges in the TM G/UI architecture, and our approaches to addressing them.

User Interface (UI) design is an iterative process that involves close liaisons between users and designers. It covers topics, ranging from usage-centered design during analysis and design, through to testing and validation, in later application lifecycle phases. This involves deriving shared principles, practices, methods and the tools to support the effective participation of different development teams in the design of a well-integrated User Interface to the SKA systems.

Currently the three core activities in this process are:

User and task analysis. Understanding what the users will do with the system;

System prototyping. Develop a series of prototypes for experimentation;

Interface evaluation. Experiment with these prototypes with users.

The TM design activity in general relies on usability prototyping as a core part of defining the design needs for the wider system. It is important to have early users' feedback in the software design and development lifecycle and also to elicit new requirements, validate existing requirements, and highlight possible critical interactions.

Within the TM UI work-stream, prototyping is also a key tool for the evaluation of technologies. Based on the lessons learned, and specific UI analysis conducted by precursor sites (MeerKAT, ASKAP, ALMA, LOFAR), a set G/UI tools has been selected and they are being analyzed against SKA TM requirements. The set includes TANGO tools (e.g. Taurus and Sardana) and general UI frameworks (such as AngularJS, Django, PyQT, PyTango, and TurboGears).

This report summarizes both some of the key principles and stages of this process and the early results from this work.

9913-163, Session PS4

Manipulating SITELLE's data: reduction, extraction, and visualization of huge hyperspectral datasets

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We present the latest development and testing results of the data manipulation suite of softwares used to handle SITELLE's data obtained at the Canada-France-Hawaii telescope (CFHT), during the commissioning run (August 2015) and the Science Verification phase (January 2016). SITELLE is an imaging Fourier transform spectrometer (iFTS), designed to obtain the spectrum of extended emission-line sources in a 11x11 arcminute field of view, with a spatial sampling of 0.32 arcsecond/pixel, in selected bandpasses of the visible range (350 - 850 nm). Large hyperspectral datasets of up to 32 Go of various objects have been obtained and successfully reduced with higher than expected speed performances. The software suite primarily used and developed with SpIOMM, a prototype installed at Mont-Mégantic, now adapted to SITELLE and integrated at CFHT is composed of IRIS, a real-time image analysis software designed to compute and display statistical facts during the observations for the CFHT remote observer; ORBS, the data reduction pipeline; ORCS, a data extraction software designed to fit models on interferometric and spectral cubes and 2D/3D viewers for real-time data exploration and analysis. Major improvements are reviewed and discussed for each software. We also show that the success of the integration at CFHT and the synergy between SITELLE's softwares relies on a simple and coherent object-oriented onion-layered architecture based on a carefully designed and versatile core module (ORB).

9913-164, Session PS4

Queue software reuse and implementation at the Large Binocular Telescope Observatory

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In this paper we detail the process the LBTO followed to chose software for reuse and modification to support binocular queue operations. We outline the survey of initial candidate solutions, how and why the final selection was made, and describe our requirements gap analysis for LBTO binocular use. We provide details of our software development approach including a project road-map and phased release strategy. We provide details of added LBTO functionality, discuss issues, and suggest some reuse lessons learned. We conclude with discussion of known desired enhancements to be addressed in future release cycles.

9913-165, Session PS4

The Infrared Imaging Spectrograph (IRIS) for TMT: data reduction system

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IRIS (InfraRed Imaging Spectrograph) is the diffraction-limited first light instrument for the Thirty Meter Telescope (TMT) that consists of a near-infrared (0.84 to 2.4 micron) imager and integral field spectrograph (IFS). The IFS makes use of a lenslet array and slicer for spatial sampling, which will be able to operate in 100's of different modes, including a combination of four plate scales from 4 milliarcseconds (mas) to 50 mas with a large range of filters and gratings. The imager will have a total field of view of 32.8 x 32.8 arcsec^2 with a plate scale of 4 mas with many selectable filters. We present the preliminary design of the data reduction system (DRS) for IRIS. Reduction of IRIS data will have unique challenges since it will provide real-time reduction and analysis of the imaging and spectroscopic data during observational sequences, as well as advanced post-processing algorithms. The DRS will support three basic modes of operation of IRIS; reducing data from the imager, the lenslet array, and slicer IFS. The DRS will include the following modules: sky/dark subtraction, correction of detector artifacts, correction of cosmic rays, flat fielding, spectral extraction, wavelength solution, cube assembly, residual atmospheric correction, flux calibration, telluric correction, PSF calibration, distortion solutions, and advanced shift and add. The DRS will be written in

Python, making use of the plethora of open-source astronomical packages available. In addition to real-time data reduction, the DRS will utilize real-time visualization tools, providing astronomers with up-to-date evaluation of the target acquisition and data quality. The Quicklook suite of tools will include visualization of the 1D, 2D, and 3D raw and reduced images. We will discuss the overall requirements of the DRS and visualization tools, as well as the necessary calibration data to achieve optimal data quality in order to exploit science cases across all cosmic distance scales.

9913-166, Session PS4

The QuickReduce data processing pipeline for the WIYN one degree imager

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The QuickReduce pipeline for the WIYN One Degree Imager (ODI) started out as a quick-look pipeline to assist with instrument commissioning, and over time evolved into the main instrument pipeline now delivering science-ready data. We will highlight several of its components that were developed especially for ODI, but can now also be applied to other wide-field imagers with one or more detectors: 1) a highly flexible cross-talk correction accounting for variations of cross-talk coefficients between detectors, source area and affected target area; 2) an efficient and effective method to derive fringing amplitude across detectors even in the presence of contaminating sources; 3) a fast, easily parallelized implementation of the la_cosmic algorithm for cosmic ray rejection. 4) a new strategy to derive a pupilghost correction template, compensating for numerous gaps in the focal plane, and powerful enough to compensate for shifts and rotation with respect to the focal plane; 5) a data association framework, allowing to trace each exposure back to its input data, and the input data back to its input data, providing full data provenance for each frame back to all contributing raw data and software components.

Combined with the optimized and highly parallelized implementation of the reduction workflow, written entirely in python, this allows generation of fully calibrated, science-ready data, as well as accompanying and describing data quality information, on a time-scale similar to that between exposures at the telescopes. We will also present changes made to the pipeline to accommodate the upgraded 5x6 detector focalplane. Finally, we illustrate where and how QuickReduce is embedded into the overall ODI dataflow, from providing quick-look data at the telescope to providing data reduction capabilities to both archive operator and archive user via the ODI Portal, Pipeline, and Archive.

9913-167, Session PS4

Key software architecture decisions for the automated planet finder

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The Automated Planet Finder (APF) at Lick Observatory on Mount Hamilton is a modern 2.4 meter computer-controlled telescope. At one Nasmyth focus is the Levy Spectrometer, at present the sole instrument used with the APF. The primary research mission of the APF and the Levy Spectrometer is high-precision Doppler spectroscopy. Observing at the APF is unattended; custom software written by diverse authors in diverse languages manage all aspects of a night's observing.

This paper will cover some of the key software architecture decisions made in the development of autonomous observing at the APF. The relevance to future projects of these decisions will be emphasized throughout.

9913-168, Session PS4

AVU/BAM: software refurbishment (design and implementation) for the CU3 gaia verification pipeline

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AVU/BAM is the Gaia software for the Astrometric Verification Unit devoted to the monitoring of the Basic Angle Monitoring (BAM), one of the metrology instruments onboard of the Gaia Payload.

AVU/BAM is integrated and operative at the Data Processing Center of Turin (DPCT), since the beginning of the Gaia Mission.

The DPCT infrastructure performs the ingestion of pre-elaborated data coming from the satellite and it's responsible of running the code of different Verification Packages.

In this paper we are presenting a structural refactoring of the code.

The new structure of the pipeline consists of three phases: the first is a pre-analysis in which a preliminary study data is performed, with the calculation of quantities needed to the analysis; the second one (configured for a parallel run on multiple nodes) processes the interferograms coming from the two Field of View of the couples of images; the third phase analyzes the data obtained from the previous processing.

Also it has been changed part of the long-term analysis and was added a phase of calibration of the data obtained from the processing.

With this new structure we achieved a significant reduction of processing time, allowing to add new analyses within the time processing constraints.

9913-169, Session PS4

Image X: new and improved image explorer for astronomical images and beyond

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The One Degree Imager - Portal, Pipeline, and Archive (ODI-PPA) has included the Image Explorer interactive image visualization tool since it went operational. Portal users were able to quickly open up several ODI images within any HTML5 capable web browser, adjust the scaling, apply color maps, and perform other basic image visualization steps typically done on a desktop client like DS9. However, the original design of the Image Explorer required lossless PNG tiles to be generated and stored for all raw and reduced ODI images thereby taking up tens of TB of spinning disk space even though a small fraction of those images (< 5%) were being accessed by portal users at any given time. It also required a heavy web application to be included within a web portal like ODI-PPA (thereby making it hard to merge in improvements made to a similar deployment in another project's portal), and served the image tiles via the Apache webserver used by the rest of the portal (which was sub-optimal). To address this and other concerns, we redesigned Image Explorer from scratch and came up with Image X, a set of microservices that are part of the Trident software suite, with extensive interactive visualization and analysis capabilities required for ODI data and beyond. We generate a full resolution JPEG image for each corresponding raw and reduced FITS image, one that can be rendered at various sizes as appropriate within the portal (for example: on tabular image listings, views allowing quick perusal of a set of thumbnails, and other initial 'image sifting' activities). Users are also able to request several layers of higher quality lossless PNG tiles similar to the ones used previously by Image Explorer version 1;

backend services pick up such requests, delegate the tile generation to an appropriate microservice while providing portal feedback to the user on the progress of this process. When ready, these tiles can be viewed in a manner similar to how users would on their desktop using a tool like DS9 without having to download Gigabytes of FITS image data. This design allows updates to the tile generation algorithms to be easily applied to any full tileset request. At any given time, only a small subset of images have full tilesets thereby dramatically decreasing the spinning disk requirements. Other improvements related to Image X include use of Docker containers to deploy backend services, use of AngularJS for the client side Model/View code (instead of depending on backend PHP Model/View/Controller code previously used), use of nginx and a lightweight NodeJS application to serve JPG and PNG tiles thereby significantly decreasing the Time To First Byte latency by a few orders of magnitude, and extension of the service for non-FITS images (for example: electron microscopy images).

9913-170, Session PS4

The ExoMars DREAMS scientific data archive

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DREAMS is the autonomous surface payload package accommodated on the ExoMars 2016 Schiaparelli Entry and Descent Module (EDM). It is a meteorological station with the additional capability to perform measurements of the electric fields close to the surface of Mars. The EDM will reach Mars during the statistical dust storm season, so DREAMS will characterize the Martian environment in this dust loaded scenario. DREAMS will perform meteorological measurements by monitoring pressure, temperature, wind speed and direction, humidity and dust opacity during a Martian sol at the landing site; characterization of the Martian boundary layer in dusty conditions; hazard monitoring by providing a comprehensive dataset to help engineers to quantify hazards for equipment and human crew: velocity of windblown dust, electrostatic charging, existence of discharges, and electromagnetic. noise potentially affecting communications, intensity of UV radiation; the first ever investigation of atmospheric electric phenomena at Mars. The DREAMS data will be archived and distributed to the scientific community through the ESA's Planetary Science Archive (PSA). All data shall be compliant with NASA's Planetary Data System (PDS4) Standards for formatting and labelling files. This paper describes the format and content of the DREAMS data, including the descriptions of the data products and associated metadata. The generation pipeline to convert raw telemetries to final products for the archive is described as well.

9913-171, Session PS4

Image processing improvement for optical observations of space debris with the TAROT telescopes

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Precise estimation of the satellites and debris trajectories is necessary to improve our knowledge of this population in order to preserve the space environment for the future. As a member of the Inter-Agency Space Debris Coordination Committee (IADC), CNES is involved in the worldwide coordination of activities related to the issues of man-made and natural debris in space. Since 2004, CNES has been observing space debris with a network of two robotic ground based fully automated telescopes called TAROT (Telescopes à Action Rapide pour les Objets Transitoires; Rapid Response Telescopes for Transient Objects). The two TAROT telescopes are fully robotic optical observatories with optimized observation scheduling, automatic data processing and archiving primarily devoted to measure the early optical counterparts of gamma-ray bursts. One of them is located in France and the second at ESO, La Silla, Chile. The system processes the data in real time. Their wide field of view is useful for the discovery, the systematic survey and for the tracking of both catalogued and un-catalogued objects. In 2008, a new image processing algorithm based on morphological mathematic was tested and implemented in the standard pipeline [1]. This method correlates the measurements of the same object on successive images and gives better detection and false alarm rates than the previous one. The overall efficiency and quality of the survey of the geostationary orbit has been drastically improved and debris detection in different orbits was then possible. Nevertheless, as the main target was the geostationary satellites, this processing was limited to the processing of images taken with telescope mount motors turned off. In those images, stars appear as horizontal streaks, geostationary objects as dots and non-geostationary objects as streaks. This algorithm was not adapted for debris observation in debris tracking mode which is the preferred mode when observing debris with a previously known orbit, mainly because of its better detectability. In this last mode, the tracked debris appears to be a point-like object and the stars appear like streaks in a diagonal direction, the direction and the length of the streaks being known. To deal with this debris tracking mode, the image processing algorithm has been recently improved by using method described in [2]. In this paper we present the adaptation to TAROT images of this algorithm composed of different processing steps: background estimation and removal, stars detection and removal, debris detection. Some new steps have been introduced to process TAROT images artefacts due to mechanical problems in the debris tracking mode. We will then present results of the newly implemented algorithm which presents improvement in terms of false detection rate and allows the new track rate mode.

[1] Bourez-Laas, M., Blanchet, G., Boër, M., Ducrotté, E., and Klotz, A. (2009). "New Algorithms for Optical Observations of Space Debris with the TAROT Telescopes". Adv. Sp. Res., 44, 1270-1278, 2009.

[2] Lévesque M.P., "Detection of Artificial Satellite in Image Acquired in Track Rate Mode", 2011 AMOS Technical Conferences, 15 Sept. 2011.

9913-172, Session PS4

The AVU/BAM usage and performances during the Gaia commissioning and early operations

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Gaia Satellite is the newest astrometric mission financed by Europe. It was launched the 19th of December 2013 and reached L2 in about 1 month. This paper describes the commissioning and early operations outcomes (first six months) of the metrology system dedicated to the Base Angle Variations output, as seen by the Astrometric Verification Unit (AVU), running at the Data Processing Center of Turin (DPCT - Italy).

Metrology results coming from the first six months of mission are slightly different from what expected.

The AVU/BAM software demonstrated to be able to cope with the different scenario.

We will describe the strong and the weak aspects of the AVU/BAM algorithms.

9913-173, Session PS4

DAS-SW: software for the characterization of H2RG detectors in Euclid NSIP instrument

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In 2020, the European Euclid satellite used to study the speed up of the universe expansion will carry the Near-Infrared Spectrometer and Photometer (NISP). This instrument is based on an array of 16 Teledyne H2RG detectors. IPNL (Nuclear Physics Institute of Lyon) is responsible to develop and validate the software of the ground characterization workflow for each of these detectors. The workflow has been designed to respect different analyzes such as dark current, noise, low and high flux. These studies must be chained and executed in 21 days per detector, this short timing induces the automatization of all the workflow, from the data acquisition to the pixels maps and characterization reports.

The Data Acquisition System Software (DAS-SW) has been developped to respect all theses requirements and especially to stored acquisition frames, the environment data and context metadata in simple, transportable container. HDF5 technology is a data model and a file format that make possible the management of all these heterogeneous complex data. For the easy way to develop and interface with other low level librairies, Python language has been choosen to manage and controll data flow.

Another major constraint is that DAS-SW must be able to run in different labs, on different characterization setups. They are composed by a cryostat controlled by a Lakeshore devices, an H2RG with its ASIC and warm electronic card associated (Teledyne SAM card or Markury Scientific board), different type of LEDs for illumination and multiple power supplies and sensors. This implies a maximum of genericity in the choice of data transport and protocol in DAS-SW environment. The Internet of Things is the chosen solution. The aim is to view all devices as a physical object connected to a local network using a simple, opened and normalized protocol such as WebSocket. It is a protocol providing full-duplex communication over a single TCP connection. WebSocket is implemented in plenty of languages and directly embedded in most major Web browsers, then it makes things easy to build clients to control, monitor, log data flow.

While WebSocket already is quite awesome, it is low-level. DAS-SW uses instead the Web Application Messaging Protocol (WAMP), which is based on WebSocket and provides two high-level communication patterns: “Remote Procedure Calls” (RPC) and “Publish & Subscribe”. WAMP enable DAS-SW to be distributed freely across process and devices according to characterization workflow functional aspects. WAMP is a routed protocol, so all messages are distributed via a router application and it avoids strong coupling between the Caller and the Callee like a basic client-server model.

On the acquisition part, DAS-SW can communicate with H2RG detector via its associated ASIC and makes a simple user API abstraction, hidding specific Warm Electronic communication and configuration.

DAS-SW Software run under Linux operating system.

9913-174, Session PS4

Thirty Meter Telescope narrow-field infrared adaptive optics system real-time controller preliminary architecture

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The Narrow Field Infrared Adaptive Optics System (NFIRAOS) is the first light AO System for the Thirty Meter Telescope (TMT). NFIRAOS is a laser guide star multi-conjugate AO (MCAO) system that corrects atmospheric and telescope image aberrations over a two arc-minute field of view in the near infrared. It will be located on the Nasmyth platform and will feed light to any one of three selectable instruments. NFIRAOS performs wavefront correction using two deformable mirrors (DM) conjugated to 0km and 11.8km, with one DM mounted on a tip/tilt stage (TTS). Within NFIRAOS are six laser guide star Shack-Hartmann wavefront sensors (LGS WFS) and one high-order natural guide star pyramid wavefront sensor (PWFS). Addition wavefront information is provided to NFIRAOS by up to three Shack-Hartmann wavefront sensors (OIWFS) located in the science instruments, and up to four on-detector guide windows (ODGW) on the science imager. Wavefront information from these detectors is processed by the NFIRAOS Real-Time Controller (RTC) to compute the DM and TTS commands. The National Research Council of Canada Herzberg, Astronomy and Astrophysics Programs (NRC-H) has developed a preliminary design for NFIRAOS RTC.

The NFIRAOS RTC is comprised of several quad-socket Linux-based servers. These servers are assigned various roles including: the High-Order Processing (HOP) servers, the Wavefront Corrector Controller (WCC) server, the Telemetry Engineering Display (TED) server, the Persistent Telemetry Storage (PTS) server, and in addition testing and spare servers.

There are up to six HOP servers that accept LGS WFS or PWFS pixels and perform parallel pixel processing and wavefront reconstruction to produce DM error vectors. The Wavefront Corrector Control (WCC) synchronizes and aggregates DM error vectors from the HOP servers and implements DM and TTS control, as well as performing low-order mode processing of OIWFS and ODGW pixels. The Telemetry Engineering Display (TED) server is the NFIRAOS RTC interface to other TMT sub-systems. The TED server receives all external commands and dispatches them to the rest of the NFIRAOS RTC servers and is responsible for aggregating several offloading and telemetry values that are reported to other sub-systems within TMT. The TED server also provides the engineering GUIs and real-time displays. The Persistent Telemetry Storage (PTS) server contains fault tolerant data storage that receives and stores telemetry data, including data for point-spread function reconstruction.

9913-175, Session PS4

FRIDA’s mechanisms control system structure and tests

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FRIDA (inFraRed Imager and Dissector for Adaptive optics) will be a near infrared imager and integral field spectrograph covering the wavelength range from 0.9 to 2.5 microns. FRIDA will work in two observing modes: direct imaging and integral field spectroscopy. In order to comply with a high level of reconfigurability FRIDA will comprise eight cryogenic mechanisms and one room temperature mechanism. Some of these mechanisms require high positioning repeatability to ensure FRIDA fulfills with high astronomical specifications. This paper presents the final design of the FRIDA mechanisms control system structure. Also, some tests performed on the most complex mechanisms in both room and cryogenic environments are described. In order to tuning up the mechanisms positioning control parameters a set of programs have been developed and tested. Programming and tuning up of the embedded control software for most of the FRIDA mechanisms has been performed.

9913-176, Session PS4

A virtual appliance as proxy pipeline for the Solar Orbiter/Metis coronagraph

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Metis is the coronagraph on board Solar Orbiter, the ESA mission devoted to the study of the Sun that will be launched in October 2018. Metis will perform imaging of the solar corona in the visible and in the UV at 121.6 nm and it is equipped with a variable retarder plate that will enable to accomplish polarimetry studies in the visible band.

Due to mission constraints and to the S/C visibility from ground, the telemetry downlink will be limited and the data will be downloaded with different delays that could reach, in the worst case, several months. In order to have a quick overview on how the operations are going on and to check the safety of the 10 on-board instruments, a dedicated downlink channel with a lower latency has been foreseen. Each instrument on board Solar Orbiter can therefore produce a restricted amount of data exploiting this high-priority link and get a feedback on its operations. The so-called Low-Latency Data will be downloaded daily and since they could trigger possible actions they have to be quickly processed on ground as soon as they are delivered.

A proper pipeline has to be developed for each instrument to deal with this data producing a tool that then will be integrated in a single system at the ESA Science Operation Center.

In order to ease the integration of the several tools in a unique system, the different teams involved on Solar Orbiter agreed to develop their tools sharing a common framework that, at the same time, leaves great flexibility to build an instrument-customised software. We chose to develop our processing tool as a Virtual Appliance, i.e. a software application that runs under a common operative system wrapped on a virtual machine. This paper will briefly provide an overview of the on board processing and data produced by Metis and it will describe the proxy-pipeline currently developed to deal with Metis low-latency data.

9913-177, Session PS4

The ALMA snooping project interface (SnooPI)

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In order to provide ALMA users with a comprehensive view of their observing projects we developed the ALMA Snooping Project Interface (SnooPI). The simple and intuitive interface allows scientists to follow the status of their projects, broken down into observing unit sets and scheduling blocks. For each scheduling block the list of execution blocks is available, including detailed observational conditions and configuration information, observations and calibration details.

The application itself contains two separate parts: a Java back-end server and a JavaScript front-end client application. The back-end server was written using Spring Boot, Spring Data and Spring Security frameworks. Spring Boot usage significantly simplifies the development process by providing default mechanisms for beans configuring, REST interfaces etc.

The front-end application was developed using small Riot framework (http://riotjs.com/) that supports routing, event management and custom tags. Although we created a so called one-page application, the Riot routing functionality allows to navigate through different views with the possibility to bookmark specific places and a correct use of back button.

At the same time the application interacts with REST interfaces of other ALMA software components to retieve information such as proposal pdf reports, project reports and quality assurance (QA) reports, observations details, as well as an interface of ticketing system to access the statistics of the user's ALMA Helpdesk tickets tickets.

From the main page one can access the list of Projects and the list of Scheduling blocks either via widgets showing the number of items in the list or from the left-hand side navigation panel. The top bar allows switching between the various regimes. By default, the application shows only active projects, i.e. projects that have been approved for observations but have not yet been delivered. Activating 'All projects' allows the user to also access all the delivered projects, from the current as well as previous observing cycles.

The "Contact scientist" mode lists all the projects a user is supporting as a Contact Scientist as well as all the projects supported by other Contact Scientists from the same ALMA Regional Centre (ARC) node (see the Proceeding of SPIE, Volume 9149, id. 91490Y (2014)).

The link behind any project code opens a pane showing the Project Code, full proposal pdf link, project grade, the name of the Contact Scientist and the node at the top. A link to the detail project report is also available.

Each project is represented as a tee-like structure with the following hierarchy: project title, proposal, Science Goal, Group and Member observing unit sets and in the lowest level, the scheduling blocks. The tree structure is identical to that shown in the ALMA Observing Tool (Proceedings of the SPIE, Volume 7019, id. 70190R (2008)). The current state of each of these entities is shown by colour icons to denote "No data taken", "Some data taken", "All data taken", "Timed out", or "Delivered". For each scheduling block the number of successful executions vs. the number of required executions is shown. Project, proposal and scheduling block rows are clickable leading to detailed view.

Each Scheduling Block detailed view contains information about array configuration, band, representative frequency, target coordinates as well as the list of execution blocks with timings, zero level QA flags and links to the QA reports.

In turn, for each execution block information on the system temperature, number of antennas, array configuration, and timings for target observations and calibrations is listed.

All this information allows users to successfully trace their observing programmes at all stages from acceptance through to data delivery.

9913-178, Session PS4

Observatory software for the Mauna Kea Spectroscopic Explorer (MSE)

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The Canada-France-Hawaii Telescope is currently in the conceptual design phase to redevelop its facility into the new Maunakea Spectroscopic Explorer (MSE). MSE is designed to be the largest non-ELT optical/NIR astronomical telescope, and will be a fully dedicated facility for multi-object spectroscopy over a broad range of spectral resolutions. This paper

outlines the software and control architecture envisioned for the new facility. The architecture will be designed around much of the existing software infrastructure currently used at CFHT as well as the latest proven open-source software. CFHT plans to minimize risk and development time by leveraging on existing technology.

9913-179, Session PS4

Synchronization of off-centered dome and 3.6 m Devasthal Optical Telescope

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Most of the optical telescopes are housed within a dome or similar structure, to protect the delicate instruments from the elements. While observing a celestial object through the telescope, the dome slit opening should be suitably positioned so that an unobstructed view of the portion of the sky is always available to the telescope. The 3.6m DOT has a cylindrical dome with a tapered roof. The telescope is placed on a pier structure which is structurally isolated from the telescope housing. The height of the dome is 9.6 m which is measured from the level of the primary mirror. The telescope has an alt-azimuth mount. In normal circumstances, synchronizing the movement of the dome with an alt-azimuth mount telescope is trivial. The dome is said to be synchronized with the telescope when the line of sight (LOS) or the optical axis of the telescope intersects with the center line of the slit at a point defined by the dome azimuth (?D) and the telescope elevation. This is true when the telescope and the dome centers coincide. However, in the case of the DOT, there is a complication to the telescope-dome geometry. The telescope is located at a distance of 1.85 m from the dome centre making an angle of 255 degrees with respect to the celestial north. This was done to facilitate the assembly of the telescope from inside the cylindrical telescope building using two 10 ton capacity cranes. In the case of 3.6 m DOT, because the telescope is off centred toward the south-west of the dome center, the LOS do not coincide. Therefore the dome azimuth corresponding to the telescope azimuth needs to be calculated taking into account the offset. Not only do we need to take into account the offset between the telescope and the dome, but, whether the line of sight is passing through the cylindrical or the roof part of the dome is also needs to be considered. When the line of sight passes through the curved surface of the cylindrical walls, we used the standard equation to get the dome positions. However, when the line of sight passes through the roof of the dome building, the dome azimuth is calculated using a set of parametric equations with the solutions considered in the true range of the dome radius. The above two conditions are combined to get the complete path of the dome when the telescope is in the track mode. An algorithm was written based on the calculations in Python language. The telescope positions are read from the Telescope control system and real time calculations are made to calculate the corresponding dome positions. A GUI has been developed also in Python to interface between the software and the micro-controller based hardware. In this poster we will be presenting the details of the calculations and the scheme that we adopted in the already implemented dome control system.

9913-180, Session PS4

A novel approach to visual rendering of astro-photographs

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When we perform a visual analysis of a cosmic object photograph the contrast plays a fundamental role. A linear distribution of the observable values is not necessarily the best possible for the human visual system (HVS). In fact HVS has not a linear response, and exploits contrast locally with different stretching for different lightness areas. As a consequence, according to the observation task, local contrast can be adapted to make easier the detection of relevant information. The information collected by a camera sensor for visual photography is fundamentally light energy distributed in a spectral interval limited by the chosen filters. This work proposes a novel approach to render physically meaningful data to make them easily observable. Final results of rendering can be presented on many different devices like monitor, printer or projector. Regardless the fact that each device can be carefully calibrated, each one retains its own characteristic transfer function and consequently potential differences in the resulting appearance.

To render an astro-photograph professional or amateur astronomers normally use Photoshop or similar image editing programs. To solve the tone mapping task of the original picture many cook-books have been proposed that are mainly based on histogram manipulation and masking techniques to modify local contrast, brightness and color. Such methods can be effective but they need a time-consuming trial and error work and the results are cumbersome to reproduce.

The proposed approach is based on Spatial Color Algorithms (SCA) that mimic the HVS behavior. These algorithms compute each pixel value by a spatial comparison with all (or a subset of) the other pixels of the image. The comparison can be implemented as a weighted difference or as a ratio product over given sampling in the neighbor region. A final mapping allows to exploit all the available dynamic range. In the case of color images SCA process separately the three chromatic channels producing an effect of color normalization, without introducing channel cross correlation. This is an important property for many needs e.g. in emission nebulae analysis.

SCA are unsupervised, they have parameters that can be tuned for specific needs, and they have shown an interesting characteristic: since local contrast is adjusted mimicking HVS mechanisms the resulting images have increased visual information content. Our approach does not exclude the use of other imaging tools for pre and/or post processing needs.

The drawback of these algorithms is a potential amplification (or addition) of the noise that has not been completely canceled in the captured images.

We will present very promising results on some images, taken from Digital Sky Survey repository and on amateur photographs of deep sky objects. The results are presented for a qualitative and subjective visual evaluation and for a quantitative evaluation through some measures, in particular to quantify the effect of algorithms on the noise.

9913-181, Session PS4

An enhanced technique for ground-based optical space debris extraction via neural networks algorithm

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The ground-based optical telescope equipped with CCD sensor have become an important tool for space debris monitoring and maintain a space debris catalogues, in order to avoid the spacecraft collision in Resident Space objects (RSO). In this paper, we emphasized on an enhancement technique for a small and dimming space object extraction. In general, the static-background subtraction are widely used to extract the moving space object in astronomy field because it is low computation time. However, the main disadvantage of this technique is not robustness with atmosphere effects, illumination changed and etc. In this research, we proposed the enhanced technique for extract the space object under complex background by using the theory of computer vision named running Gaussian average and adaptive it by neural networks algorithm to find the optimal learning rate automatically. The advantage of our propose algorithm is not only to suppress the background noise, low

computation cost but also without a burden or bias from the human, when stellar background has independently changed in image sequences. The performance of proposed algorithm is evaluated by the experimental results with real image, show that our proposed algorithm can achieve a high level of Signal-to-Clutter Ratio (SCR) under a complex or dynamic-background.

9913-45, Session 10

TMT approach to observatory software development process *(Invited Paper)*

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The purpose of the Observatory Software System (OSW) is to integrate all software and hardware components of the Thirty Meter Telescope (TMT) to enable observations and data capture; thus it is a complex software system that is defined by four principal software subsystems: Common Software (CSW), Executive Software (ESW), Data Management System (DMS) and Science Operations Support System (SOSS), all of which have interdependencies with the observatory control systems and data acquisition systems. Therefore, the software development process and plan must consider dependencies to other subsystems, manage architecture, interfaces and design, manage software scope and complexity, and standardize and optimize use of resources and tools. Additionally, the TMT Observatory Software will largely be developed in India through TMT's workshare relationship with the India TMT Coordination Centre (ITCC) and use of Indian software industry vendors, which adds complexity and challenges to the software development process, communication and coordination of activities and priorities as well as measuring performance and managing quality and risk. The software project management challenge for the TMT OSW is thus a multi-faceted technical, managerial, communications and interpersonal relations challenge. The approach TMT is using to manage this multi-faceted challenge is a combination of establishing an effective geographically distributed software team (Integrated Product Team) with strong project management and technical leadership provided by the TMT Project Office and the ITCC partner to manage plans, process, performance, risk and quality, and to facilitate effective communications; establishing an effective cross-functional software management team composed of stakeholders, OSW leadership and ITCC leadership to manage dependencies and software release plans, technical complexities and change to approved interfaces, architecture, design and tool set, and to facilitate effective communications; adopting an agile-based software development process across the observatory to enable frequent software releases to help mitigate subsystem interdependencies; defining concise scope and work packages for each of the OSW subsystems to facilitate effective outsourcing of software deliverables to the ITCC partner, and to enable performance monitoring and risk management. At this stage, the architecture and high-level design of the software system has been established and reviewed. During construction each subsystem will have a final design phase with reviews, followed by implementation and testing. The results of the TMT approach to the Observatory Software development process will only be preliminary at the time of the submittal of this paper, but it is anticipated that the early results will be a favorable indication of progress. TMT is scheduled to achieve first-light in 2024 and start observatory operations soon thereafter.

9913-46, Session 10

Don't get taken by surprise: planning for software obsolescence management at the ALMA Observatory

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The ALMA observatory is gearing up for full operations, and while most parts of the ALMA software are still being very actively developed and improved, some of the underlying technologies, third-party tools and hardware, as well as parts of the ALMA software itself are already showing signs of age. This is no big surprise after well over a decade of development in the rapidly changing world of software engineering. But it needs to be managed proactively to avoid small issues becoming big problems in the long run. An obsolescence management plan should come to help.

For hardware to be maintained having a solid obsolescence management plan is very common and many good examples and practices to follow can easily be found. For software this does not seem to be the case. While the core principles of establishing and maintaining a bill of materials, performing risk analysis, prioritization and mitigation can be taken over from hardware in a very similar fashion, many of the considerations to be taken into account for assessing the probabilities and risks are very different for software.

Based on well-established obsolescence management practices for hardware, we present an approach to tackle the problem of software obsolescence management for the ALMA observatory. This is not only important to keep our software maintainable for the lifetime of the ALMA observatory as the environment around us evolves and changes, but also to avoid falling victim to the urge for never-ending rewriting, refactoring and replacement.

We hope that this paper will help others in a similar situation to become aware of the need for software obsolescence management and perhaps benefit from our ideas and findings, and maybe more so to help establishing an active dialog between projects and organizations to mutually benefit from each other.

9913-47, Session 10

Management of the science ground segment for the Euclid mission

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Euclid is the second medium-sized mission (M2) of the ESA Cosmic Vision 2015-2025 Plan, aimed at understanding the nature of dark energy and dark matter by accurately measuring the accelerated expansion of the Universe. By measuring two probes (weak lensing and baryon acoustic oscillations) simultaneously, Euclid will constrain dark energy, general relativity, dark matter and the initial conditions of the Universe with unprecedented accuracy. The mission will observe galaxies and clusters of galaxies out to z~2, in a wide extra-galactic survey covering 15 000 deg?,

plus a deep survey covering an area of 40 deg?. The payload is composed of two instruments, an imager in the visible domain (VIS) and an imager-spectrometer (NISP) covering the near-infrared. The launch is planned in Q4 of 2020.

The Science Operations Centre (SOC) operated by ESA and nine Science Data Centres (SDCs), provided by a Consortium composed of 14 European countries (Austria, Belgium, Denmark, Finland, France, Germany, Italy, the Netherlands, Norway, Portugal, Romania, Spain, Switzerland, United Kingdom) plus the United States, are the elements of the Euclid Science Ground Segment (SGS). ESA/SOC and the Euclid Consortium have developed, and are committed to maintain, a tight collaboration in order to design and develop a single, cost-efficient and truly integrated SGS. The distributed nature, the size of the data set, and the needed accuracy of the results are the main challenges expected in the design and implementation of the SGS. In particular, the huge volume of data (not only Euclid data but also ground based data) to be processed in the SDCs will require a distributed storage to avoid data migration across SDCs.

Since data management will be performed in a distributed environment, the Euclid SGS organisation is based on collaborative software development, virtualization, distributed processing and a data-centric approach to the system architecture, implying quite a complexity in the design and implementation of the data handling and processing facilities.

There are therefore a set of management challenges that the Euclid SGS will need to face in dealing with such complexity. The main aspect is related to the organisation of a geographically-distributed software development team. In principle algorithms and code is developed in a large number of institutes, while data is actually processed at fewer centres (the national SDCs) where the operational computational infrastructures are maintained. The effort in designing and implementing the SGS is focussed on the core products and on minimising complexity (with the purpose of minimising risks and costs as well). There is an aim at enforcing commonality wherever needed (mainly at the data structures level, where the need for a common data and information system has been identified). In the few cases where commonality cannot be achieved, interfaces are defined.

In this framework, quality control plays a crucial role. The software produced for data handling, processing and analysis is built within a common development environment defined by an SGS System Team, which has been already active for several years. The code is built incrementally through different levels of maturity going from prototypes, developed mainly by scientists, to production code, engineered and tested at the SDCs. A number of incremental challenges (infrastructure, data processing and integrated) have been included in the Euclid SGS test plan to verify the correctness and accuracy of the developed systems.

9913-48, Session 10

Software collaboration between the observatory and the instrument development teams at the JCMT and UKIRT

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When an instrument team builds a modern, common user, astronomical instrument for an observatory, there are many software issues that need to be settled. Typically there is a need for instrument control software at the hardware-software interface; integration software so that the instrument can be controlled from the observatory's control system (OCS); engineering (control and analysis) software so the instrument can be developed and tested without a full blown OCS; changes to the OCS to accommodate new observing modes to utilize the unique capabilities of the new instrument; perhaps new capabilities to other existing parts of the observatory such as scan patterns for the telescope or the secondary mirror; and, definitely not least, data reduction software that can overcome the drawbacks of the instrument to push it to attain its full potential. Eventually all of this software will be supported by the observatory, so they must supply a set of guidelines for the instrument team to follow. But the instrument team are the ones who know the instrument best, so their input is necessary also. This paper discusses the approach that has been followed by the JCMT and UKIRT telescopes over the past 15 years while accepting new instruments. It discusses what worked, what did not work, the areas in which the required effort was significantly underestimated, and those in which large amounts of time were spent on developing capabilities that were never used. A summary proposes a work breakdown, documentation required from both sides, and the proper amount of (and timing of) collaboration between the instrument team and the observatory.

9913-49, Session 10

Building a world-wide open source community around a software framework: progress, dos, and don'ts

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As we all know too well, building up a collaborative community around a software infrastructure is not easy. Besides recruiting enthusiasts to work as part of it, mostly for free, to succeed you also need to overcome a number of technical, sociological, and, to our surprise, some political hurdles.

The ALMA Common Software (ACS) was developed at ESO and partner institutions over the course of more than 15 years. While it was mainly intended for the ALMA Observatory, it was early on thought as a generic distributed control framework. ACS has been periodically released to the public through an LGPL license, which encouraged around a dozen non-ALMA institutions to make use of ACS for both industrial and educational applications. In recent years, the Cherenkov Telescope Array and the LLAMA Observatory have also decided to adopt the framework for their own control systems.

The aim of the "ACS Community" is to support independent initiatives in making use of the ACS framework and to further contribute to its development. The Community provides access to a growing network of volunteers eager to develop ACS in areas that are not necessarily in ALMA's interests, and/or were not within the original system scope. Current examples are: support for additional OS platforms, extension of supported hardware interfaces, a public code repository and a build farm. The ACS Community makes use of existing collaborations with Chilean and Brazilian universities, reaching out to promising engineers in the making. At the same time, projects actively using ACS have committed valuable resources to assist the Community's work. Well established training programs like the ACS Workshops are also being continued through the Community's work.

This paper aims to give a detailed account of the ongoing (second) journey towards establishing a world-wide open source collaboration around ACS. The ACS Community is growing into a horizontal partnership across a non centralised and diverse group of actors, and we are excited about its technical and human potential.

9913-50, Session 11

The new Gemini Observatory archive: a fast and low cost observatory data archive running in the cloud

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We have recently developed and deployed a new data archive for the Gemini Observatory.

Focused on simplicity and ease of use, the archive web interface provides a number of powerful and novel features such as complete and automatic association of calibration data with the science data it applies to, and the ability to bookmark searches. More conventional features of note include user authentication and access control over proprietary data, the availability of JPEG data previews within the web interface, and of course searching the data collection by a number of parameters covering instrument configuration, object being observed, and observation details such as the date and time of observation and program and dataset types and identifiers. A simple but powerful API allows programmatic search and download of data. The system is designed to meet the needs of PIs and public archive users as well as remote observers and eavesdropping PIs, with a responsive interface and new data being available for download from the archive typically less than a minute after the readout completes.

By focusing on the most common use cases from our community, and leveraging cloud computing and open-source software, we have implemented a complete facility archive service in a 2-year, 3-FTE development phase, and with an annual operating cost of approximately US$6k + 0.5-FTE. All legacy data has been transferred into the new system, and raw data is ingested in near-real time from both Gemini telescopes. The total compressed data volume is currently a little over 8 TB.

The archive is hosted “in the cloud” on a commercial cloud computing platform (Amazon Web Services), which provides us internet connectivity beyond what we could reasonably achieve locally and also provides us significant cost savings in both operations and development over more traditional deployment options. The code is written in python, utilizing a PostgreSQL database and Apache web server, and is designed such that it can use cloud storage or the file-system to store the content and thus can be deployed either on a commercial cloud computing platform or on a more traditional physical or virtual machine. The same code is deployed at our telescope sites to provide local data management facilities, which includes transferring data to the public archive system in the cloud. This flexibility also provides us with several options to deploy larger scale or multiple servers should the need arise, including the option to deploy archive servers within academic institutions or other user community centers if necessary.

9913-51, Session 11

Petascale cyber infrastructure for ground-based solar physics: approach of the DKIST data center

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When construction is complete in 2019, the Daniel K. Inouye Solar Telescope will be the most-capable large aperture, high-resolution, multi-instrument solar physics facility in the world. The telescope is designed as a 4-m off-axis Gregorian, with a rotating Coude laboratory housing and supporting five first-light imaging and spectropolarimetric instruments capable of simultaneous operation. At current design, the facility and its instruments will generate data volumes of 5 PB, produce 10^8 images, and 10^10 metadata elements annually. This data will not only forge new understanding of solar phenomena at high resolution, but enhance participation in solar physics and further grow a small but vibrant international community.

The DKIST Data Center is being designed to store, curate, and process this flood of information, while augmenting its value by providing association of science data and metadata to its acquisition and processing provenance. Starting in early Operations, the Data Center will produce quality-controlled and -assured calibrated data sets, closely linked to facility and instrument performance during the Operations lifecycle. These data sets will be made available to the community openly and freely, with software and algorithms made available through community repositories like Github for further collaboration and improvement.

We discuss the current design and key facets of the DKIST Data Center, focusing on the need to provide highly-available and reliable computational and data storage systems on a shoestring, and the underappreciated challenges of calibrating ground-based solar data. We conclude by describing the crucial integration of the Data Center within the larger DKIST Operations lifecycle, and how software and hardware support, intelligently deployed, will enable high-caliber solar physics research and community growth for the DKIST’s 40-year lifespan.

9913-53, Session 11

TRIDENT: scalable compute archive, visualization, and analysis systems

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The Astronomy scientific community has embraced Big Data processing challenges, e.g. associated with time-domain astronomy, and come up with a variety of novel and efficient data processing solutions. However, data processing is only a small part of the Big Data challenge. Efficient knowledge discovery and scientific advancement in the Big Data era requires new and equally efficient tools: modern user interfaces for searching, identifying and viewing data online without direct access to the data; tracking of data provenance; searching, plotting and analyzing metadata; interactive visual analysis, especially of (time-dependent) image data; and the ability to execute pipelines on supercomputing resources with minimal user overhead and understandable even to novice users. The Trident project at Indiana University offers a comprehensive web- and cloud-based framework of frameworks that can be configured and refactored into customized Scalable Compute Archive (SCA) systems including extensive visualization and analysis capabilities. Trident seamlessly scales up or down in terms of data volumes and computational needs, and the user interface feature sets within the web portal can be quickly adapted to meet individual project requirements. It uses a micro-services architecture, and is made up of light-weight services connected by a message bus; a web portal built using Twitter/Bootstrap, AngularJS, and HighCharts JavaScript libraries, and backend services written in NodeJS, PHP/Zend, and Python. The Trident microservice software suite consists of (1) a Progress service to monitor workflows and sub-workflows (for eg., a complex pipeline data processing job that executes several steps on a set of images) (2) ImageX, an image preview and analysis service that allows interactive image analysis via highly compressed JPEG images for rough perusal and on-demand generation of lossless PNG images for more complex visualization analysis. (3) an authentication service allowing password logins, and hooks to other single sign-on services (4) a Notification service that serves statistical collation and reporting needs of various projects. (5) several others under development. Trident also has built-in frameworks offering: collections for data grouping and sorting, metadata plotting tools, and a Tier-2 workflow system that enables rapid integration of data processing pipelines on an associated compute cluster with customized user interfaces. Trident is an umbrella project, spun off from the One Degree Imager - Portal, Pipeline, and Archive (ODI-PPA) project, and thus far has been deployed toward 1) a powerful analysis/visualization portal for Globular Cluster System (GCS) survey data collected by IU researchers, 2) a data search and download portal for the IU Electron Microscopy Center's data (EMC-PPA), 3) a metadata quality control and analytics portal for DICOM formatted medical imaging data prodoced by the IU Radiology Center's medical imagers, 4) a limited set of components to serve GIS data within the IU GIS web portal, 5) a prototype archive for the Ludwig Maximilian University's Wide Field Imager. Trident SCA systems leverage supercomputing and storage resources at Indiana University but can be configured to make use of any cloud/grid resource, from local workstations/servers to (inter)national supercomputing facilities such as XSEDE.

9913-54, Session 11

The NOAO data lab virtual storage system

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Collaborative research and computing environments are essential for working with the next generations of large astronomical data sets. A key component of them is a cloud storage system to enable data hosting, sharing, and publication. VOSpace is a lightweight interface that provides network access to arbitrary backend storage solutions and is endorsed by the IVOA. Although similar APIs exist, such as Amazon S3, WebDav, and Dropbox, VOSpace has several advantages for research applications. It is designed to be protocol agnostic, it is focused on data control operations, and it supports asynchronous and third-party data transfers, thereby minimizing unnecessary data transfers. It also allows arbitrary computations to be triggered as a result of a transfer operation, a feature known as a Capability. For example, a file can be automatically ingested into a database when put into an active directory, or a data reduction task, such as Sextractor, can be run on it. In this talk, we shall describe the VOSpace implementations that we have developed for the NOAO Data Lab. These offer both dedicated remote storage, accessible as a local filesystem via FUSE, and a local VOSpace service to easily enable data synchronization. We also make extensive use of the Capability mechanism to support data workflows.

9913-119, Session 11

Cloud services on an astronomy data center

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The research on computational methods for astronomy performed by the first phase of the Chilean Virtual Observatory (ChiVO) led to the development of functional prototypes, implementing state-of-the-art computational methods and proposing new algorithms and techniques.

The ChiVO software architecture is based on the use of the IVOA protocols and standards. These protocols and standards are grouped in layers, with emphasis on the application and data layers, because their basic standards define the minimum operation that a VO should conduct. As momentary verification, the current implementation works with a set of data, with 1 TB capacity, which comes from the reduction of the cycle 0 of ALMA.

This research was mainly focused on spectroscopic data cubes coming from the cycle 0 ALMA's public data. As the dataset size increases when the cycle 1 ALMA's public data is also increasing every month, data processing is becoming a major bottleneck for scientific research in astronomy.

When designing the ChiVO, we focused on improving both computation and I/O costs, and this led us to configure a data center with 424 high speed cores of 2,6 GHz, 1 PB of storage (distributed in hard disk drives-HDD and solid state drive-SSD) and high speed communication Infiniband.

We are developing a cloud based e-infraestructure for ChiVO services, in order to have a coherent framework for developing novel webservices for on-line data processing in the ChiVO. We are currently parallelizing these new algorithms and techniques using HPC tools to speed up big data processing, and we will report our results in terms of data size, data distribution, number of cores and response time, in order to compare different processing and storage configurations.

9913-55, Session 12

Mount control software of the ASTRI SST-2M prototype for the Cherenkov Telescope Array

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A mini-array of nine ASTRI telescopes has been proposed to be installed at the southern site of the CTA.

The ASTRI SST-2M telescope is an end-to-end prototype proposed for the Small Size class of Telescopes of the future Cherenkov Telescope Array (CTA).

The prototype is installed in Italy at the INAF observing station located at Serra La Nave on Mount Etna (Sicily) and it was inaugurated on September 2014.

The Mount Control System of the ASTRI SST-2M prototype comprises all hardware and software components devoted to control the drive system, to perform telescope slewing and tracking, to monitor the status of all the devices mounted on the telescope (e.g. the Camera, the Active Mirrors control) and to manage the safety of the system (interlock chain).

The Mount Control Software installed on the ASTRI SST-2M telescope prototype makes use of standard and widely-deployed industrial hardware and software. The state of the art of the control and automation industries was selected, in order to have the highest technological performance with the maximum assembly compactness, high reliability and reduced maintenance. The software package was implemented with the TwinCAT environment for the software Programmable Logical Controller (PLC), while the electronics of control have been chosen in order to maximize the homogeneity and the real-time performance of the system.

From this point of view ASTRI is one of the very few examples where all the functions, including the generation of the tracking trajectory of the telescope, are managed through software PLCs. This choice makes the ASTRI SST-2M telescope an efficient and stand-alone machine, easily integrated in CTA.

The ASTRI SST-2M mount control and security systems have pushed to the limit the cutting-edge technology applied, they allow us to test for the first time a lot of functionality developed by the selected companies, and they serve as prototype for the future Mount Control System of the ASTRI mini-array telescopes proposed to be installed at the CTA southern site.

9913-56, Session 12

Automation and control of the MMT thermal system

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Automated control of the thermal ventilation system for the MMT Observatory (MMTO) 6.5-meter primary mirror (M1) began in 2009 after years of manual control by the telescope operator. This automated control combines: 1) a simple linear regression control algorithm between the primary chiller setpoint for the glycol/water coolant and the discharge ventilation air temperature into the M1 mirror cell, and 2) a differential air temperature controller for a second methanol-based chiller that trims the final discharge air temperature. The thermal control system attempts to drive the M1 glass temperature towards the ambient air temperature while minimizing thermal gradients within the mirror.

These algorithms are based upon data gathered prior to 2009 during manual control of the thermal system. A rich set of environmental and thermal data has been acquired under automated control over the past six years. The success of the current control algorithms will be evaluated towards the dual goals of minimizing the air/glass temperature contrast at the front face of M1 and reducing thermal gradients within the mirror.

Beginning in 2015, new heating, ventilation, and air conditioning (HVAC) equipment has been installed and brought on?line at the MMTO. This new equipment includes a larger glycol-based chiller, variable frequency drives (VFDs) for the main M1 ventilation blower motor, larger glycol coolant pumps, multiple three-way glycol mixing valves, extensive new coolant plumbing, and numerous status and temperature remote sensors and controllers. This upgraded facilities/building HVAC hardware must be integrated with automated control of the M1 ventilation system. The new HVAC and associated hardware at the MMTO is embedded with electronics, software, sensors and network connectivity that allow these devices to collect and exchange data with each other and with centralized facility automation systems.

The open-source, industry-standard BACnet (Building Automation and Control network) protocol is used to communicate via BACnet objects between devices and computers on different physical data layers. A summary is presented of the BACnet network topology and integration of this protocol into the existing MMTO telemetry and control system, including Redis key-?value stores and MySQL relational databases. The new M1 ventilation and facilities HVAC systems require a more complex and robust approach to automation and control. Instead of control via adjusting chiller setpoints, the ventilation air will be conditioned through the more widely used approach of mixing warm and cold glycol coolant through multiple three-way valves, each associated with an air/glycol heat exchanger. This approach provides better overall system response. Linear regression and other statistical and machine learning approaches as well as proportional-?integral-?derivative (PID) controllers are considered for the revised automated M1 ventilation and facilities HVAC control system.

Finally, new graphical user interfaces (GUI's) have been developed to allow the user to monitor and control the upgraded MMTO thermal system, including the M1 ventilation and facilities HVAC subsystems. These GUI's allow manual control of the thermal system as well as monitoring of automated control of the system. Real-time updates of environmental and thermal data are provided to users using current web-based technologies.

9913-57, Session 12

Software detailed design of INO340 telescope control system

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The INO340 telescope is a 3.4m Alt-Az reflecting optical telescope with a 0.3° field-of-view and the F?ratio of Cassegrain focus is f/11. It is currently in the middle of the detailed design phase. In astronomical projects, software architecture plays an important role because many subsystems and components from different sources with different implementations aspects must work together in a consistent and reliable way. Software architecture deals with the design and implementation of the high-level structure of the software. It shall be designed in a way that it could satisfy the major functionality and performance requirements of the system, as well as some other, non-functional requirements such as reliability, scalability, portability, and availability.

To describe INO340 telescope control system (INOCS) software architecture, we utilize a model called "4+1", composed of multiple views or perspectives. This model has been used with success on many large telescope projects with some local customization and adjustment in terminology. In order to address challenging architectures like ours, the model is made up of five main views:

• The logical view, which is the object model of the design

• The process view, which captures the concurrency and synchronization aspects of the design

• The development view, which describes the static organization of the software in its development environment

• The physical view, which describes the mapping(s) of the software onto the hardware and reflects its distributed aspect

• The scenario view, which binds the previous four views.

We have studied the software architecture model of several telescope control systems including GMT, GTC, DCT, TMT, SOAR, VLT, VST and ATST. We have found that they have also followed the concepts of "4+1" model in their detailed design phase with some customizations. Not all software architecture need the full "4+1" views therefore some of these decided that they do not need to include all of the aforesaid five views in their architecture model.

In INOCS, we have considered all five views in order to obtain a comprehensive software architecture model. The views are used to describe the system from the viewpoint of different stakeholders, such as end-users (observers and operators), developers and project managers. The logical view supports behavioral requirements which are the services the system should provide to INOCS users. The process view takes into account some requirements such as performance and system availability. The development view focuses on the organization of the software modules in the software development environment. The physical view takes into account the system's requirements such as reliability and scalability. We have mapped the views into a set of UML diagrams and some additional visual charts in order to model INOCS software architecture.

In this paper, we review the software architecture of major telescope control systems. Subsequently, we will illustrate the architecture model of INOCS based on the "4+1" view model using the corresponding UML diagrams and other explanatory visual charts such as the class, sequence, component, deployment and use case diagrams respectively. In the last section, we will present a brief description about the INOCS development process in terms of software architecture in detailed design phase.

9913-58, Session 12

Introduction to FAST central control system

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Five-hundred-meter Aperture Spherical Telescope (FAST) will be the largest single dish radio telescope in the world. The construction will be accomplished in September, 2016. During observation, parts of the spherical reflector deforms to a paraboloid of revolution and feed is placed at the instant focal point by 6 parallel cables and fine-tuned by AB rotator and Stewart manipulator. The relative control, measurement and monitor subsystems of active reflector, feed support and receiver should work synchronously, which makes telescope control complicated and inconvenient for operators.

Therefore, an autonomous central control system is designed and implemented to connect and coordinate all subsystems. The main functions are collecting and managing observation tasks, translating the tasks into commands and sending to subsystems, gathering and storing operation data, monitoring facility status and providing time service. In central control room, a large screen display system is employed to show the main status of telescope and can be switched to show a combination of any interested client desktop screens and closed-circuit television signals. Additionally, a friendly web-based user interface is developed for operator, engineer and scientist users. The technique makes it easy to expand the ability of remote operation.

In this paper, the software and hardware architecture of FAST central control system will be presented. The relative infrastructure such as electric power, network and site buildings will be described. Finally, the expansion and upgrades issues will be discussed.

9913-59, Session 12

Prototyping the E-ELT M1 local control system communication infrastructure

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The primary mirror of the E-ELT is composed of 798 hexagonal segments of about 1.45 metres across. Each segment can be moved in piston and tip-tilt using three position actuators and therefore can compensate for perturbations, mainly due to temperature, gravity and wind forces. Inductive edge sensors are used to provide feedback for global reconstruction of the mirror shape.

The E-ELT M1 Local Control System will provide a deterministic infrastructure for collecting edge sensor and actuators readings and distribute the new position actuator references while at the same time providing failure detection, isolation and notification, synchronization generation and distribution to segment subunits, power and networking monitoring and configuration management.

The main characteristic of the communication architecture design is the fact that the measurements from each of the 798 segments subunits arrive from the field electronics as individual network packets without relying on intermediate custom data aggregation or pre-processing. The design is based on UDP/IP over switched ethernet communication and relies on multicast addressing, 10Gbps bandwidth and multicore architecture at the computer room.

The prototype mock-up is composed by a server, mirror position data simulator and networking infrastructure replicating the most critical part, in terms of timing and data flow, of the E-ELT M1 control system design.

The simulated M1 segment position measurements are generated using a NI LabVIEW PXI equipped with 6 dual port FPGA based ethernet boards. The measurement messages are triggered by the arrival of the synchronization packet.

The M1LCU was running VxWorks on an Intel multi core server, it implemented the M1 figure loop data flow and generated the synchronization UDP multicast packet at 500 Hz.

The M1 figure loop is implemented as a three pipelined staged algorithm: positions measurements collection, references computation and references distribution.

The present paper describes the prototyping activities carried out to verify the feasibility of the E-ELT M1 control system communication architecture design and assess its performance and potential limitations.

9913-60, Session 12

A new telescope control software for the Mayall 4-meter telescope

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The Mayall 4-meter telescope at Kitt Peak National Observatory, USA, recently went through a major modernization of its telescope control system. We describe MPK (Mayall Pointing Kernel), our new software for telescope control. MPK outputs a 20Hz position-based trajectory with a velocity component, which feeds into Mayall's new servo system over a socket. We wrote a simple yet realistic servo simulator that let us develop MPK mostly without access to real hardware, and also lets us provide other teams with a Mayall simulator as test bed for development of new instruments. MPK has a small core comprised of prioritized, soft realtime threads that handle the critical tasks. Access to the core's services is via MPK's main thread, a complete, interactive Tcl/Tk shell, which gives us the power and flexibility of a scripting language to add any other features, from GUIs, to an API for instrument clients over the network, to interaction with critical subsystems like dome or guider. MPK is designed for long term maintainability: it runs on stock Linux OS and computer, and uses only standard, open source libraries, except for commercial software that comes with source code in ANSI C/C++. Mayall's modernization was based on that of its sister telescope, the Blanco 4-meter at Cerro Tololo Inter-American Observatory, in Chile. MPK uses the same core libraries as its Blanco counterpart: TCSpk/TPK, the commercial libraries for astrometry and pointing by Patrick Wallace and David Terrett, and Reflexxes, an open source trajectory generator. But instead of modifying Blanco's telescope control software, we wrote MPK from scratch, because a thorough, in-house understanding of the control software was crucial for meeting the performance requirements and for being able to quickly add custom, complex features requested by instrument scientists. Besides, although Mayall and Blanco are mechanically similar, their existing, and upcoming, subsystems are different enough to make writing from scratch worthwhile in the long run. We discuss the technical details of how MPK combines Reflexxes with TCSpk/TPK to generically handle any motion request, from slews to offsets to sidereal or non-sidereal tracking. We also discuss our Tpoint modeling strategy.

9913-61, Session 13

Revisiting software specification and design for large astronomy projects
(Invited Paper)

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The separation of science and engineering in the delivery of software systems overlooks the true nature of the problem being solved and the organization that will solve it. Use of a systems engineering approach to managing the requirements flow between these two groups as between a customer and contractor has been used with varying degrees of success by well-known entities such as the U.S. Department of Defense. However, treating science as the customer and engineering as the contractor has unfavorable consequences that can be avoided and opportunities that are missed. For example the “problem” being solved is only partially specified through the requirements generation process since it focuses on detailed specification guiding the parties to a technical solution. Equally important is the portion of the problem that will be solved through the definition of processes and staff interacting through them. This interchange between people and processes is often underrepresented and under appreciated.

Indeed, the natural tendency is for requirements to serve as the primary means of communication between parties where changes necessitate reconciliation and typically leave both sides looking out for their own interests. There is another way afforded to an organization that staffs its own engineering team(s) such as those commonly found in astronomy facility development projects such as the DKIST Operations Tools and Data Center project. Such projects face a common theme of highly talented and motivated scientists and engineers that may be insulated from understanding each other’s goals working within constraints in budget and schedule.

By concentrating on the whole problem and collaborating on a strategy for its solution a science implementing organization can realize the benefits of driving towards common goals (not just requirements) and a cohesive solution to the entire problem. The initial phase of any project when well executed is often the most difficult yet most critical and thus it is essential to employ a methodology that reinforces collaboration and leverages the full suite of capabilities within the team. This paper describes a holistic approach to specifying the needs induced by a problem, its solution, and the roles played by the stakeholders during the specification and development of the solution.

9913-62, Session 13

Software requirements flowdown and preliminary software design for the G-CLEF spectrograph

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The GMT-Consortium Large Earth Finder (G-CLEF) is a fiber-fed optical echelle spectrograph that will be the first light instrument on the Giant Magellan Telescope (GMT). While G-CLEF is general-purpose instrument, with multiple observing modes capable of addressing many fundamental questions in the areas of stellar astrophysics and cosmological studies, the precision radial velocity (PRV) mode (R ~ 110,000) that is designed for exoplanet science drives much of the instrument design. When operating in the PRV mode, G-CLEF will provide unprecedented radial velocity sensitivity, with the capability of making single PRV measurements with a precision of 40-50 cm/sec, and an ultimate PRV sensitivity requirement of 10 cm/sec from multiple observations.

Such PRV sensitivity is achieved by maintaining the G-CLEF optical bench in an ultra-stable environment that is immune to mechanical perturbations, either intrinsically by design (e.g., vibration isolation), or through active control by software (e.g., thermal control, active leveling). These factors drive the flow-down to the software requirements and preliminary design of the instrument device control software (IDCS), and significantly increase the complexity of the latter. In addition to the typical mechanical and detector subsystems, the IDCS must manage an active precision thermal control system that maintains the optical bench temperature to +/- 1 mK, and a precision active leveling system that ensures that the spectrograph assembly is maintained in a gravity invariant orientation with a precision of a few micro-radians. The IDCS must monitor telemetry from several hundred sensors and manage more than one hundred controllable devices. In addition to instrument control, achieving the specified radial velocity precision requires the use of data reduction algorithms that are carefully matched to the instrument operational concept in order to fully eliminate common sources of calibratable errors and minimize the impact of non-calibratable and systematic errors.

To ensure tight integration with the GMT software systems, the G-CLEF software uses a model-based software engineering approach and conforms to a reference architecture developed by the GMT Organization. While model-based development is commonly used for large scale industrial robotics systems, this approach has not been utilized widely in the development of ground-based astronomical instrumentation, where the focus is typically on the hardware. However, in the era of billion-dollar extremely large telescopes, and their concomitant operating costs, expectations for first light performance raise the bar for software development scope and schedule to near space-borne mission standards.

In this paper, we describe the approaches that we have used to identify and flow down the requirements for the G-CLEF IDCS and data reduction pipeline software, and discuss the preliminary designs for key components. Since this phase of the G-CLEF software effort is being conducted in parallel with both the internal G-CLEF hardware design work and also with the GMT’s own software requirements and design effort, we discuss how we handle revisions to driving requirements that impact our software requirements and preliminary design process. Finally, we identify a number of lessons learned that have general applicability to the development of software for ground-based instrumentation under similar circumstances.

9913-63, Session 13

Software framework for automatic learning of telescope operation

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The “Gran Telescopio de Canarias” (GTC) is an optical-infrared 10-meter segmented mirror telescope at the ORM observatory in Canary Islands (Spain). The GTC Control System (GCS) is a distributed object and component oriented system based on RT-CORBA and it is responsible for the operation of the telescope, including its instrumentation. The current development state of GCS is mature and fully operational. On the one hand telescope users as PI’s implement the sequences of observing modes of future scientific instruments that will be installed in the telescope and operators, in turn, design their own sequences for maintenance. On the other hand engineers develop new components that provide new functionality required by the system. This great work effort is possible to minimize so that costs are reduced, especially if one considers that software maintenance is the most expensive phase along the software life cycle. Could we design a system that allows the progressive assimilation of sequences of operation and maintenance of the telescope, through an automatic self-programming system, so that it can evolve from one Component oriented organization to a Service oriented organization? One possible way to achieve this is to use mechanisms of learning and knowledge consolidation to reduce to the minimum expression the effort to convert the specifications of the different telescope users to the operational deployments. This article presents the key to make this process a reality: refactoring based on value, Self-Organizing Maps, Service Oriented Architectures, Adaptive software and evolutionary algorithms.

9913-64, Session 13

Can your software engineer program your PLC?

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The use of Programmable Logic Controllers (PLCs) in the control of large physics experiments is biquitous. The programming of these controllers is normally the domain of engineers with a background in electronics, this paper introduces PLC program development from the software engineer's perspective.

LC programs provide the link between control software running on PC architecture systems and physical hardware controlled and monitored by digital and analogue signals. The higher-level oftware running on the PC is typically responsible for accepting operator input and from this deciding when and how hardware connected to the PLC is controlled. The PLC accepts demands from the PC, considers the current state of its connected hardware and if correct to do so (based upon interlocks or other constraints) adjusts its hardware I/O signals appropriately for the PC's demands. A published ICD (Interface Control Document) defines the PLC memory locations available to be written and read by the PC to control and monitor the hardware. Historically the method of programming PLCs has been ladder diagrams that closely resemble circuit diagrams, however, PLC manufacturers nowadays also provide, and promote, the use of higher-level programming languages.

Based on techniques used in the development of high-level PC software to control PLCs for multiple telescopes, this paper examines the development of PLC programs to operate the hardware of a medical cyclotron beamline controlled from a PC using the Experimental Physics and Industrial Control System (EPICS), which is also widely used in telescope control. The PLC used is the new generation Siemens S7-1200 programmed using Siemens' Pascal based Structured Control Language CL). The approach described is that from a software engineer's perspective, utilising Siemens' Totally Integrated Automation (TIA) Portal development environment to create modular PLC programs based upon reusable functions capable of being unit tested without the PLC connected to hardware. Emphasis has been placed on designing an interface between EPICS and SCL that enforces correct operation of hardware through stringent separation of EPICS accessible PLC memory and hardware I/O addresses used only by the PLC. The paper also introduces the method used to automate the creation, from the same source document, the PLC memory structure (tag) definitions defining memory used to access hardware I/O and that accessed by EPICS) and creation of EPICS database records used to access the PLC addresses. From direct experience this paper demonstrates the advantages of PLC program development being shared between electronic and software engineers, to enable use of the most appropriate processes from both the perspective of the hardware and the higher-level software used to control it.

9913-65, Session 13

A lightweight set of frameworks for the implementation of state analysis in the GMT control system

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The Giant Magellan Telescope (GMT) requires the implementation of complex behaviors to perform observations in both seeing limited and adaptive optics modes. GMT is developing a set of software frameworks that facilitate the specification and development of the required behaviors. The frameworks are the embodiment of a state analysis control architecture, the design and implementation of which is enabled by a model based development process and a set of Domain Specific Languages (DSL).

The behaviors needed to achieve the required image quality in each observing mode will involve complex target acquisition sequences of multiple wavefront and metrology sensors and the coordination of complex nested control loops. The robust execution of these behaviors and a visual representation of the system that can be understood intuitively by the telescope operators are both paramount to the accurate and efficient operation of the observatory.

The implementation of the frameworks leverages existing open-source third party packages, and remain implementation independent following an adapter pattern.

The design of these frameworks addresses several concerns related to distribute communication, goal based sequencing, data product provenance, and complex behavior visualization. A common core framework implements a distributed communication design pattern to establish temporal bindings of arbitrary duration between goals and state variables. This communication pattern provides a higher level abstraction than publish-subscribe or command-reply patterns and simplifies the implementation of complex distributed goal networks. Observations will be specified with a goal-based sequencing DSL that represents the desired behavior of the system. A goal engine will execute the sequences and record the relevant state variables. The sampled data will provide evidence of past behavior of the system and will enable the reenactment of that behavior for diagnostics purposes. The record of sampled data will also provide the foundation to establish data product provenance as well as temporal and causal dependencies to facilitate the understanding of state variable telemetry. Finally, a visualization framework that facilitates the navigation and monitoring of complex goal networks enables telescope operators to understand and anticipate the behavior of the system.

9913-66, Session 14

Integrated data analysis in the age of precision spectroscopy: the ESPRESSO case

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The Echelle SPectrograph for Rocky Exoplanets and Stable Spectral Observations (ESPRESSO) is an ultra-stable spectrograph for the coudé-combined focus of the VLT. With its unprecedented capabilities (resolution up to ~200,000, wavelength range from 380 to 780 nm; centimeter-per-second accuracy in wavelength calibration), ESPRESSO is a prime example of the now spreading "science machine" concept: a fully-integrated system carefully designed to perform direct scientific measurements on the data, in a matter of minutes from the execution of the observations. This approach is motivated by the very specific science cases of the instrument (search for terrestrial exoplanets with the radial velocity method; measure of the variation of fundamental constants using the spectral signatures of the inter-galactic medium) and is achieved by a dedicated tool for spectral analysis, the data analysis software (DAS), targeted to both stellar and quasar spectra. In this paper, we describe characteristics and performances of the DAS, with particular emphasis on the novel algorithms for quasar analysis (continuum fitting and interpretation of the absorption features), and its relevance for future instrumentation (like the high-resolution spectrograph for the E-ELT).

9913-67, Session 14

Fast and flexible big data processing at LSST data rates using existing, shared-use hardware

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Processing astronomical data to science-readiness was and remains a challenge, in particular in the case of multi-detector instruments such as wide-field imagers. One such instrument, the WIYN One Degree Imager, is available to the astronomical community at large, and, in order to be scientifically useful to its varied user-community on a short timescale, provides its users fully calibrated data in addition to the underlying raw data. However, time-efficient re-processing of the often large datasets with improved calibration data and/or software requires more than just a large number of CPU-cores and disk space. This is particularly relevant if all computing resources are general purpose and shared with a large number of users in a typical university setup. Our approach to address this challenge is a flexible framework, combining the best of both high performance (large number of nodes, internal communication) and high throughput (flexible/variable number of nodes, no dedicated hardware) computing. Based on the Advanced Message Queuing Protocol, we a developed a Server-Manager-Worker framework. In addition to the server directing the workflow and the worker executing the actual work, the manager maintains a list of available worker, adds and/or removes individual workers from the worker pool, and re-assigns worker to different tasks. This provides the flexibility of optimizing the worker pool to the current task and workload, improves load balancing, and makes the most efficient use of the available resources. We present performance benchmarks and scaling tests, showing that, today and using existing, commodity shared-use hardware we can process ODI data with data throughputs (including data reduction and calibration) approaching that expected in the early 2020s for future observatories such as the Large Synoptic Survey Telescope.

9913-68, Session 14

GAVIP: a platform for Gaia data analysis

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Gaia is a major ESA mission currently in orbit around L2. Its main scientific objective is to survey one billion stars in the Milky Way in order to make a 3-D map of unprecedented accuracy, thereby answering fundamental questions about the origin and evolution of our Galaxy. The distances of about 10 million stars will be determined to better than 1% accuracy.

In the course of its survey, Gaia also observes tens of thousands of other objects, such as asteroids, brown dwarfs and extra-solar planets. With its unique combination of wide field of view, sensitivity, simultaneous source colours/spectra and multi-epoch observations, Gaia's archive will undoubtedly become a transformational resource across many branches of astronomy in the years and decades to come. The first Gaia data release is scheduled for mid-2016.

Although Gaia has a 1 billion pixel focal plane instrument, the Gaia archive will primarily be in the form of a catalogue, rather than image-based. Even so, the final Gaia archive will ultimately be of the order of 1 PetaByte in size. As Gaia data becomes publicly available and reaches a wider audience, there is therefore an increasing need to facilitate the further use of Gaia products without needing to download large datasets over the net.

The Gaia Added Value Interface Platform (GAVIP) is designed to address this need by providing an innovative platform for scientists to re-use and deploy, close to the data, their own existing code - packaged as "Added Value Interfaces" (AVIs).

AVIs, when hosted in GAVIP, comprise a set of processing elements that can be shared and combined into more complex scientific workflows. GAVIP hosts these AVIs using Docker containers, which provide a lightweight form of virtualisation. The container itself is created using one of many Docker images, referred to as 'AVI templates', which are created to support different types of development. For example, a Java runtime may be installed in a template to enable the use of Java within an AVI pipeline.

Each AVI is developed within a Python framework which integrates a rich toolkit that astronomers are familiar with, including Jupyter and libraries such as astroquery, numpy and scipy.

In addition to hosting user-contributed AVIs, GAVIP will provide features including search and retrieval of products from the Gaia archive, management of user-specified processing tasks, management and storage of processing outputs and provision of services to integrate resources using VOSpace, TAP and SAMP.

GAVIP leverages technologies including OS-level virtualization (via Docker) and pipelines defined by code (via Luigi).

This paper will describe the capabilities of GAVIP, focussing on the features affecting users of the GAVIP platform. A demonstration of GAVIP can be provided.

GAVIP is designed to provide flexible and innovative capabilities for scientists and others to remotely engage with the Gaia archive, and is therefore to be deployed initially close to the primary data-products (i.e. Gaia data products), at the European Space Astronomy Centre (ESAC), near Madrid. This platform may also provide a useful baseline for future 'big astronomy' projects such as LSST.

Conference 9914: Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII

Tuesday - Friday 28–1 July 2016

Part of Proceedings of SPIE Vol. 9914 Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VII

9914-1, Session 1

The NIKA 2 commissioning campaign: performance and first results

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New challenges in millimetre wave astronomy require high sensitivity and high resolution instruments. To achieve such a goal, the development of a new generation of array of detectors is needed, because current detectors such as high impedance bolometers are already photon noise limited both for space and for ground observations. One of the proposed technological solution is the use of Lumped Element Kinetic Inductance Detectors (LEKID) that allow for a large multiplexing factor (up to 400 pixels) frequency domaine read-out and an accessible manufacturing. This technological solution has been selected for the NIKA project that aims at constructing a dual-band millimetre camera for observation at 30 m IRAM telescope (Pico Veleta, Spain).

Within this context, the NIKA 2 camera is a kilo-pixels arrays instrument and it represents a one step further with respect the NIKA pathfinder instrument which has already shown state-of-the-art detectors and photometric performance. The camera has been permanently installed at the IRAM 30m telescope in October 2015, and it will be open to public observations at the end of 2016. The targets of the NIKA2 camera are to perform simultaneous observations in two millimetre bands (1.15 mm and 2.0 mm) of sub-mJy point sources as well as to map extended continuum emission up to about 6.5 arcmin scale with diffraction limited resolution and background limited performances. Such observational requirements will lead the NIKA2 camera to be a science driver in several astrophysical fields as the follow-up of Planck satellite clusters via the Sunyaev-Zel'dovich effect, high redshift sources and quasars, early stages of star formation and nearby galaxies emission. In addition, The NIKA 2 instrument hosts polarisation capability in the 1.15 mm arrays. The adopted solution is the use of an rotating warm Half-Wave-Plate to modulate the astrophysical polarised signal and a polariser mounted at the 100 mK stage to analyse the linear polarisations on the two 1.15 mm arrays.

9914-2, Session 1

POL-2: a polarimeter for the James-Clerk-Maxwell Telescope

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A polarimeter for SCUBA-2 has been under commissioning at the JCMT for some time. We will describe some recent results and the behavior of the instrument. The instrument consists of a spinning achromatic lambda/2 plate followed by a wire-grid analyzer in front of the SCUBA-2 bolometer camera. Observations are done by scanning the telescope. The polarization signal is dominated by the background polarized by the optical components and the wind blind protecting the telescope. We will discuss the removal of this polarized background as well as its relation to the instrumental polarization. Reflections between the analyzer and wave plate generate a modulation with twice the wave plate rotation rate which overshadows the polarization modulation at four times the wave plate rotation rate. The instrumental polarization is due to the wind screen and oblique reflections in the optical train. These and other artifacts due to the SQUID readout in SCUBA-2 are discussed as well as the data reduction.

9914-3, Session 1

ZEUS-2 at APEX: science results and performance

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We present recent science results from the second generation Redshift (z) and Early Universe Spectrometer (ZEUS-2) deployed at the Atacama Pathfinder Experiment (APEX) Telescope. ZEUS-2 is a long slit, direct detection, grating spectrometer for submillimeter wavelengths. The detector consists of two TES bolometer arrays designed for use between 200-850um. It is optimized for observations of faint molecular and atomic emission lines (R~1000) that can be used to characterize the physical conditions of both nearby and highly redshifted galaxies.

ZEUS-2 has demonstrated background limited performance in both, 350um and 450um bands at the telescope enabling extremely sensitive ground based sub-mm spectroscopy. Most of the star formation in the early Universe is highly obscured by dust in the interstellar medium of the host galaxy. A large population of such dusty star forming galaxies (DSFGs) in the early Universe has been discovered through their far-IR continuum (redshifted to sub-mm bands). Spectral line studies can help reveal the mode of star formation and characterize the energy source powering the starburst in individual sources. We present first results of our survey of the bright [OIII] 88um line studying the young stellar populations in such DSFGs, during the epoch of maximum star formation rate density in the Universe. We also present the first high redshift (z>2) detection of the [OI] 63um line from a galaxy at z=4.6.

We will also report on the lab characterization of the new 215/645um array to be deployed simultaneously with the 400um array in ZEUS-2 for the next observing run at APEX. The sensitivity of ZEUS-2's TES bolometer arrays, filters tuned to various grating orders and 7 atmospheric telluric windows combined with the 12-m APEX telescope at the best accessible site for sub-mm astronomy provides a powerful combination for studying galaxy formation and evolution near and far. ZEUS-2 observations will provide a stepping stone for detailed studies of high-z galaxies with ALMA in the near future.

9914-4, Session 1

The ArTeMiS wide-field submillimeter camera: on-sky performances at 350 and 450 microns

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ArTeMiS is a wide-field submillimeter ground-based camera with simultaneous imaging capabilities in two atmospheric transmission bands (350 and 450 microns), and a radiometric mode in the 200 microns band. It benefits from the exceptional conditions at the APEX telescope site (Chile, 5100m above sea level), in term of low atmospheric opacity in the submillimeter range. ArTeMiS is developed by CEA (Saclay and Grenoble, France), IAS (France) and the University of Manchester (UK) in collaboration with the European Southern Observatory (ESO). The camera has been previously tested at APEX during two technical runs in 2013 and 2014, with detectors operating in the 350 microns atmospheric window only. The paper reports on the installation of the full capacity ArTeMiS instrument during the first half of 2016 in the Cassegrain cabin of the APEX telescope.

The first part of the paper gives an overview of the updated hardware of ArTeMiS. We present several improvements in the mechanical and optical parts compared to the previous version. We describe the addition of the new optical bands, in particular the 200 μm band to be used to reduce atmospheric noise. The updated cryogenic system is also presented: we describe the thermal regulation system that improves the overall stability of the detectors during observations. This new feature is of particular interest when we perform skydips (measurement of the atmospheric emission at different airmasses). During these phases, the telescope rapidly moves along the elevation axis and this sudden change in orientation can affect the performances of the ArTeMiS pulse tubes (and therefore the temperatures of the whole thermal chain). The thermal regulation can actively compensate the variations of temperatures of certain thermal interfaces inside the camera.

We also describe the characteristics of the focal plane units: pixel yield, spatial arrangement of the pixels, optical alignment, dynamical range, flatfield. The ArTeMiS detectors consist in resistive high impedance bolometers arranged in 16 x 18 sub-arrays operating at 300 mK. These detectors are similar to the ones developed for the Herschel PACS photometer but they are adapted to the high optical load encountered at APEX site.

In the last section, we give details on the on-sky commissioning run made at APEX. Performances on sky are given and compared to the results obtained during the previous runs. The mapping speed of the previous version of ArTeMiS was already 3 times better than the previous 350 microns instrument installed at APEX. We give the updated value and show preliminary scientific results.

9914-5, Session 1

MUSTANG2: on-sky performance and first results

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MUSTANG2 is a 215 element focal plane array that operates between 75 and 105 GHz on the 100 meter Green Bank Telescope (GBT). It shares many of the science goals of its predecessor, MUSTANG, which operated between 2007 and 2013. However, with over 10 times the sensitivity and an increase in the field-of-view (fov) of over a factor of 25, MUSTANG2 will greatly expand on what MUSTANG has been able to do. For example, MUSTANG was able to resolve substructure in selected galaxy clusters via the Sunyeav-Zel'dovich effect but with 100 times the mapping speed MUSTANG2 will be able to do the same on a statistically significant sample. In addition MUSTANG2's larger fov (4.3 arcminute) will recover angular scales from 9" to 6' with high fidelity providing a unique and larger overlap between high resolution instruments such as ALMA and lower resolution single dish telescopes such as ACT or SPT.

MUSTANG2 will have a background limited performance. Smooth walled feeds with monotonically decreasing profiles control the illumination of the telescope and planar OMTs couple each polarization into superconducting microstrip. To simplify readout and to make detector noise targets easier to meet, the two polarizations are combined onto a single TES bolometer. To read out the detectors, MUSTANG2 uses microwave SQUID multiplexers and is the first astronomical instrument to do so. In this multiplexing scheme the TES bias current runs through an RF SQUID which forms part of a resonator. Changes in incident power on the TES change the self-inductance of the SQUID, which in turn causes small shifts in the frequency of the resonator. These shifts can be measured by a matching RF frequency tone. Each resonator in the array has a slightly different frequency so large numbers of detectors can be read out using a comb of tones sent into the cryostat using a single pair of coaxial lines.

Because of the large size of the GBT, the optimal feed horn pitch is 15.5mm which is large compared to the size of the silicon wafers used to manufacture TES detectors. Consequently MUSTANG2 uses a modular approach with individual detectors mounted on the end of each feed and connected to the multiplexers via a superconducting circuit board. This has the advantage that a completely functioning array can be achieved and new detector recipes tested simply by swapping out modules.

9914-22, Session 1

SPACEKIDS: kinetic inductance detectors for space applications

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Superconducting detectors operating at sub-kelvin temperatures are currently the most sensitive detectors of far infrared and submillimetre radiation. Instruments using transition edge superconducting (TES) sensors and kinetic inductance detectors (KIDs) are already in use in ground-based

astronomical instruments, but have yet to be flown in space. SPACEKIDS, a recently completed European Union FP-7 project, has focussed on developing advanced KID arrays and demonstrating their suitability for space applications in both astronomy and Earth observing.

SPACEKIDS has included the following activities: (i) review and analysis of the scientific requirements for future astrophysics observatories, cosmic background polarisation experiments, and Earth observing missions, to derive key requirements for different applications and to specify the design of laboratory demonstration systems and the performance parameters of prototype arrays; (ii) development and evaluation of various pixel and array designs using both antenna-coupled and lumped-element KID architectures; (iii) design and manufacture of 2-GHz bandwidth readout electronics suitable for use with kilo-pixel KID arrays; (iv) fabrication and comprehensive testing, in representative laboratory test-beds, of prototype kilo-pixel arrays operating in both low and high photon background, to demonstrate key performance parameters relevant to future space missions; (v) conceptual studies of space-borne KID-based instruments and formulation of a technology development roadmap outlining future work needed to develop space-qualified KID array systems.

Following an in-depth study of future mission requirements, detailed performance specifications were defined for two demonstrator systems (one low-background, representative of a cold-aperture space astrophysics mission) and one high-background (representative of Earth-observing applications), including electromagnetic radiation bandwidth, background power levels, sensitivity (NEP), 1/f noise, speed of response, cosmic ray susceptibility, crosstalk rejection, dynamic range and linearity. There has been a wide range of modelling and experimental work, with good progress made in all respects. Modelling of KID-KID cross-coupling has quantified the degree to which it depends on inter-pixel distance and on the differences in resonant frequency, leading to the development and verification of a method to minimise the effects, and showing that KID arrays can be made with negligible cross coupling. KIDs based on aluminium films have been shown to meet the sensitivity and other requirements, with photon noise limited performance down to background power levels of 0.1 fW and ability to achieve high-efficiency broadband optical coupling. Methods of reducing the susceptibility of the detectors to cosmic ray impacts have been modelled and experimentally proven. Both antenna-coupled and lumped-element KID array designs have been developed, manufactured and successfully tested in dedicated high- and low-background test facilities, using the FPGA-based readout electronics developed and built for the project.

We will present an overview of the SPACEKIDS project and a summary of its main results and conclusions.

9914-6, Session 2

Optical performance of prototype horn-coupled TES bolometer arrays for SAFARI

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The next generation of far-infrared space-based astronomical observatories will require extremely sensitive detectors. To meet the challenge of testing such sensitive detectors we constructed an ultra-low background test facility based on a cryogen-free high-capacity dilution refrigerator, paying careful attention to stray-light exclusion, shielding, and vibration isolation. This test facility has been used for optical testing of ultra-sensitive prototype horn-coupled TES bolmeters for SAFARI, the grating spectrometer on board the proposed SPICA satellite. SAFARI's three bolometer arrays, coupled with a diffraction grating, will make spectroscopic observations over the wavelength range 34—210 μm.

Each of SAFARI's prototype bolometers consists of a transition edge sensor (TES), with a transition temperature close to 100 mK, and a tantalum absorber on a thermally-isolated silicon nitride membrane. The nitride membrane sits behind a few-moded feedhorn and in front of a hemispherical backshort. SAFARI requires extremely sensitive detectors (NEP<0.2 aW/rtHz), with correspondingly low saturation powers, to take advantage of SPICA's cooled optics.

For optical measurements the SAFARI Detector Test Facility contains internal cold (3—35 K) and hot (up to ~300 K) black-body calibration sources, a light pipe for external illumination, and a broad-band reference detector for characterising the spectral content of the calibration sources. Following a long programme of optimization and characterization the test facility is in routine use, measuring the electrical and optical characteristics of ultra-sensitive TES bolometers with NEP as low as 0.5 aW/rtHz.

We measured the broad-band response of prototype detectors for SAFARI's short-wave band (34--60 μm) under DC bias and obtained a thorough understanding of how the detectors couple to the modes supported by the feedhorn. We have also used an external Fourier transform spectrometer with the light pipe to measure the spectral response of the detectors.

We have added reimaging optics to the test bed in order to facilitate array optical measurements. We are now using the SAFARI Detector Test Facility for optical testing of prototype detector arrays read out with frequency-domain multiplexing. We present our latest measurements of the optical performance of prototype arrays, compare them with simulations, and discuss them in terms of the instrument performance.

9914-7, Session 2

Optical characterization of a camera module developed for ultra-low NEP TES detector arrays at FIR wavelengths

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A unique camera architecture is proposed for future FIR low background instruments using ultra-low noise TES detectors. It consists of using profiled wall pyramidal horns in a square array feeding an array of TES detectors on a single silicon chip with an appropriate back-short. Important factors which drive this design are the need for a compact form with robust structure and tight tolerances <5?m which creates a Faraday cage around the detectors and guards against stray light. Here we report on the optical design and on the spectral-spatial characterisation of a small 16 pixel camera. The prototype uses TES detectors with NEPs ~10-16 W/Hz0.5 which have been fabricated with near identical optical coupling structures to mimic their much lower NEP counterparts (~10-19 W/Hz0.5). This modification, which is achieved through changing only the pixel thermal conductance, G, has allowed us to perform spectral/spatial cryogenic testing using a 100mK Adiabatic Demagnetisation Refrigerator to view room temperature thermal sources. The measurements show a flat spectral response across the waveband and minimal side lobe structure in the antenna patterns down to 30dB.

In addition, to separate coupling efficiency issues attributable to either the detector or the horn plate we have devised a scheme that enables spectral and spatial measurements of the horn plates alone to be made at ambient temperature. These results are also reported here.

9914-8, Session 2

Performance of horn-coupled transition edge sensors for L- and S-band optical detection on the SAFARI instrument

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We describe the geometry, architecture, dark- and optical performance of ultra-low-noise transition edge sensors as THz detectors for the SAFARI instrument. The TESs are fabricated from superconducting Mo/Au bilayers coupled to impedance-matched superconducting beta-phase Ta thin-film absorbers. The detectors have phonon-limited dark noise equivalent powers of order 0.5-1 “aW”⁄√(“Hz”) and saturation powers of order 20-40” fW.” The low temperature test configuration incorporating micro-machined backshorts is also described, and construction and typical performance characteristics for the optical load are shown. We report preliminary measurements of the optical performance of these TESs for two SAFARI bands; L-band at 110-210 “?m” and S-band 34-60 “?m” .

9914-9, Session 2

Ultra-low noise TES bolometer arrays for SAFARI instrument on SPICA

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SPICA (SPace Infrared telescope for Cosmology and Astrophysics) is a future space mission for mid- and far-infrared (IR) astronomy. By having a large (2.5 m) and cooled (< 8 K) telescope combined with ultra-sensitive IR detectors, SPICA provides an opportunity to make natural background-limited observations over the wavelength range from 17 to 230 μm. One of the instruments aboard SPICA is SAFARI (SpicA FAR-infrared Instrument), which is a grating spectrometer covering the full 34-230 μm wavelength range. SAFARI detectors are transition edge sensor (TES) bolometers for three wavelength bands: S-band for 34-60 μm, M-band for 60-110 μm, and L-band for 110-230 μm. Each band requires a large number of pixels (~ 600-2000 pixels) and an extremely-high sensitivity (electrical Noise Equivalent Power, NEPel ~ 2?10^-19 W/√Hz at frequencies below ~ 100 Hz). SRON is developing ultra-low noise TESs based on a superconducting Ti/Au bilayer on a suspended SiN island with SiN legs. The pixel size is ~ 800x800 μm^2. Three types of TESs were fabricated on SiN islands with different sizes and with and without optical absorbers. These TESs have thin (0.20 μm), narrow (0.5-0.7 μm), and long (340-460 μm) SiN legs, and show Tc of ~ 93 mK and Rn of ~ 158 m. They were characterized under AC bias using a Frequency-Division Multiplexing readout (1-3 MHz) system. The TESs without absorber show NEPs as low as 1.1?10^-19 W/√Hz with response time of below 1 ms,. For the TESs with absorber, we confirmed a higher NEPel (~ 5?10^-19 W/√Hz) than that of TESs without the absorber, due to the stray light.

9914-10, Session 2

Development and performance of the microwave SQUID multiplexed TES array for MUSTANG-2

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MUSTANG-2 is a 90 GHz feedhorn-coupled, microwave SQUID-multiplexed TES bolometer array, with 215 unpolarized pixels. MUSTANG-2 operates with background-limited performance and 9” resolution on the 100-meter Robert C. Byrd Green Bank Telescope in Green Bank, WV. The sensitivity and mapping speed provided by MUSTANG-2 on the GBT will allow detailed study of a myriad of astrophysical phenomena including galaxy cluster mergers, active galactic nuclei, and star formation. In addition, MUSTANG-2 will enable detailed follow-up of galaxy clusters detected by Planck, ACT-Pol, and others in order to better constrain the scaling relationship between cluster mass and flux from the Sunyaev-Zel’dovich effect. The microstrip-coupled detector technology utilized for MUSTANG-2 was developed by a collaboration consisting of NIST, Princeton, the University of Chicago, the University of Colorado, and the University of Michigan. The collaboration has already produced detectors that have been thoroughly tested and deployed on SPTpol, ACTpol, and ABS. The microwave SQUID readout system developed for MUSTANG2 will eventually allow thousands of detectors to be read out with a single pair of coaxial cables. This microwave SQUID multiplexer combines the proven abilities of millimeterwave TES detectors with the multiplexing capabilities of KIDs with no degradation in noise performance of the detectors. In this system each TES is coupled to an RF-SQUID. A change in TES current (caused by the TES absorbing incident photons) induces a change in the magnetic flux of the SQUID, which then shifts the resonant frequency of resonator inductively coupled to that SQUID. The chain of resonators is then interrogated with a comb of probe tones whose transmitted amplitude and phase trace the power incident on the TES. Each multiplexing device is read out using warm electronics consisting of a commercially available ROACH board, a DAC/ADC card, and an Intermediate Frequency mixer circuit. The hardware was originally developed by the UC Berkeley Collaboration for Astronomy Signal Processing and Electronic Research (CASPER) group, whose primary goal is to develop scalable FPGA-based hardware with the flexibility to be used

in a wide range of radio signal processing applications. We present on the design and performance of the MUSTANG-2 array, including the microwave SQUID multiplexed devices as well as the readout system and results from commissioning of MUSTANG2.

9914-11, Session 2

Silicon-based antenna-coupled polarization sensitive millimeter-wave bolometer arrays for cosmic microwave background instruments

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We are developing feedhorn-coupled polarization-sensitive detector arrays that utilize monocrystalline silicon as the dielectric material for the on-chip microwave circuitry. Monocrystalline silicon has a low-loss tangent and repeatable dielectric constant, characteristics that allow efficient and uniform superconducting microwave circuits to be realized. An additional advantage of this material is its low specific heat that is well defined by the Debye equation. In a detector pixel, two Transition-Edge Sensor (TES) bolometers are antenna-coupled to in-band radiation via a symmetric planar orthomode transducer (OMT). The orthogonal linear polarizations are coupled to superconducting microstrip transmission lines. On-chip filtering is employed to both reject out-of-band radiation from the upper-band edge to the gap frequency of the niobium superconductor, and to flexibly define the bandwidth for each TES to meet the requirements of the application. The full-waveguide bandwidth of the OMT can be divided with a diplexer to achieve high-fidelity multichroic operation when desired. Metalized silicon platelets are used to define the quarter-wave backshort for the symmetric waveguide probes. This micro-machined structure is also used to mitigate the coupling of out-of-band radiation to the microwave circuit. At 40 GHz, the detectors achieve ~90% coupling efficiency with a linear TES response to in-band radiation. In this paper, we describe the development of the 90 GHz detector arrays that will soon be demonstrated using the Cosmology Large Angular Scale Surveyor (CLASS) ground-based telescope.

9914-12, Session 3

Development of digital sideband separating receivers for YTLA

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This report presents a digital sideband separating method of upgrading the heterodyne receivers of the Yuan-Tseh Lee Array (YTLA) to a two-sideband receiver system. As observations of the Sunyaev-Zeldovich (SZ) clusters tapered off, a new initiative was taken for the YTLA, formerly the Array for Microwave Background Anisotropy (AMiBA), to map CO intensity to trace the large scale structure of star forming galaxies in the early universe. Since the analog correlator for the SZ observations doesn't have enough frequency resolution, the array is being retrofitted with a digital correlator for molecular line detection. Digital sideband separating receivers were also developed to double the processing bandwidth to probe more space volume. The receiver has a MMIC HEMT front-end operating at 3mm wavelength, and outputs signals at intermediate frequencies(IF) of 2-18 GHz. Our sideband separation scheme utilizes an analog RF hybrid followed by mixers as down-converters. The IF hybrid is implemented using high-speed analog?to?digital converters (ADC) and field?programmable gate arrays (FPGA). The ADC is capable of sampling up to 5 giga-sample-per-second (Gsps) and designed to interface with the Re-configurable Open Architecture Computing Hardware (ROACH), a stand-alone FPGA processing board developed by the Collaboration for Astronomy Signal Processing and Electronics Research (CASPER). The design samples up to 4 Gsps and thus produces two sidebands, each with 2 GHz bandwidth. This 2 x 2GHz band can be tuned within the 2-18 GHz IF of the array. By equalizing power and delay between the in-phase and quadrature (I/Q) signals, the sideband rejection ratios (SRR) are above 20 dB across the 4 GHz bandwidth. SRRs above 30 dB can be achieved when calibration is applied.

9914-13, Session 3

A wideband 240 GHz receiver for the submillimeter array

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Over the past few years, the Submillimeter Array (SMA) has offered 3 receiver bands for observation: the 200 GHz receiver covers 200 – 245 GHz; the 300 GHz receiver covers 260 – 350 GHz; and the 400 receiver covers 330 – 420 GHz. While the SIS mixers at the heart of these receivers can be operated over much wider bandwidth, the above listed useful bandwidth is dictated by the lowestt common denominator of frequency of operation of the Gunn oscillators powering the individual receivers in each antenna of the SMA.

Recently, a new receiver band has been introduced at the SMA. This new 240 GHz receiver is operated by a YIG-based Local Oscillator which is continuously tunable between 210 and 270 GHz. The new receiver is part of the wideband upgrade effort of the SMA, undertaken since 2011, in which the 8 element interferometer targets to increase its digital processing bandwidth from 4 GHz DSB to 2 x 8 GHz DSB for its 28 baselines of observation. For this, the SMA has expanded its IF bandwidth from 4 – 8 GHz to 4 – 12 GHz, while offering dual band and dual polarization observation capabilities. As a result, the SMA-240 receiver can be tuned to receive any sky frequency covering 198 – 282 GHz.

Apart from the wide IF bandwidth, the receiver features a low cost local oscillator module based on commercial components, built around an 8 – 18 GHz YIG oscillator and a 23 – 30 GHz medium power amplifier. No further high frequency power amplification is used. The SIS mixer is a scaled version of other SMA receivers. By using a 3 junction series connected SIS mixer, the receiver can provide low noise IF to beyond 12 GHz. The performance of this new receiver is comparable to that of the SMA-200 receiver already in operation. Including all the SMA receiver optics, typical receiver noise temperatures of 40 – 50 K are readily achieved across the whole receiver bandwidth. The noise measurement also demonstrates that the YIG-based LO does not degrade the receiver sensitivity.

One key mission of the SMA-240 receiver is to operate in conjunction with the SMA-200 receiver, by means of a wire grid polarizer at ambient temperature, to provide dual polarization observations. It is therefore important that the beams from the two receivers are co-aligned. During the commissioning phase of the SMA-240 receiver, we have employed a compact scanner built around a multiplied noise source to perform in situ amplitude beam mapping of the two receivers at the first focal plane of the SMA optics train. This set up allows quick alignment of the receiver beams.

In this paper, we will report on the construction of the SMA-240 receiver and its local oscillator module, it's on- telescope performance and the procedure used to align the receiver beams.

9914-14, Session 3

A new high-performance sideband-separating mixer for 650 GHz

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In the past we successfully demonstrated a sideband-separating mixer for the frequency range of 600-720 GHz (ALMA Band 9). This mixer is based on the classical quadrature hybrid architecture, micromachined into a modular waveguide split-block. This mixer fulfilled the ALMA specifications with respect to noise temperature and image rejection.

However, based on the performance of the individual mixer devices, the performance was expected to be better. The main issues were a general excess of noise temperature, and a marked anti-correlation of the noise temperature and image rejection between mixer blocks of different materials and surface finish.

We report on the mechanisms responsible for these effects, and conclude the following. In the first place, the anti-correlation of the noise temperature and the image rejection is explained by the presence of standing waves. Based on simulations, we know the rejection ratio to be very sensitive to those. In principle, all potential round-trip paths should be terminated in matched loads, so no standing waves can develop. In practice, imperfect loads and non-negligible input/output reflections of the other components give many opportunities for standing waves. Since we can attribute almost all loss of rejection to the presence of standing waves, the anti-correlation with the noise temperature becomes obvious: when there is excess loss in the structure, the waveguides start acting like distribured loads, reducing the standing waves, and thereby improving the rejection ration. At the same time, however, the noise temperature suffers.

For the observed excess loss, two main contributions were identified: material properties and waveguide geometry. On the side of material properties, the gold plating that is customarily applied to waveguide blocks appeared to be detrimental to the waveguide transmission. In contrast, we found the noise performance of unplated copper blocks (even when alloyed with a few percent of tellurium for machinability) to be much better. The second important loss mechanism turned out to be the geometry of the waveguides. These were rather small (310 x 145um), which put the lower edge of the band close to the waveguide cutoff.

While functionally excellent, what was not taken into account at the time was the behaviour of the losses as function of waveguide size. A run of simulations we performed shows that this is close to the cutoff, losses rise significantly even with high-conductivity waveguide walls.

Based on these experiences, we designed a completely new waveguide structure, with a basic waveguide size of 400 x 200um and improved loads. As mentioned before, a strong emphasis was placed on low input and output reflections, in some places at the cost of phase or amplitude imbalance, for which there is ample marging in the design, however. Apart from further details of the design, we present the first results of the new mixers, tested in a modified production-level ALMA band 9 receiver.

9914-16, Session 3

Sideband-separating MMIC receivers for observation in the 3mm band

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Until April, 2015, CARMA, the Combined Array for Research in Millimeter-wave Astronomy, provided observational facilities in the 1-cm, 3-mm, and 1-mm bands. The receivers in the 3-mm band were single-polarization, double-sideband SIS mixers with cooled MMIC IF amplifiers, delivering 8 GHz of instantaneous bandwidth. During the final proposal funding period, we developed a new generation of receiver based on 3-mm MMIC amplifiers followed by image separating mixers capable of delivering 17 GHz of bandwidth in each sideband in each of two polarizations, or 68 GHz total instantaneous bandwidth per antenna. We present the design and results for the prototype receiver.

The goal was to develop low-noise receivers covering the 3-mm band from 80-116 GHz. To convert the signal down to a usable band, a side-band separating mixer is used after the amplifiers. Its function is to separate the noise from the two sidebands at a level of > 10 dB for improved sensitivity; much higher separation of the signal is achieved by phase-switching the LO in the interferometer.

Each amplifier is an integrated block incorporating three MMIC chips, waveguide input and output probes, and gain slope equalizers, as well as an integrated bias protection circuit. Using measured s-parameters for the MMICs and an EM model of the blocks, the equalizer parameters were adjusted for optimum amplifier performance. Measurements of the first demonstration blocks show an amplifier noise temperature between 25 and 45 K across the 75-116 GHz band, with 45-55 dB gain.

The amplifier is followed by a sideband-separating mixer designed for this receiver. It uses a waveguide quadrature hybrid to split the input signal, which is then fed to a pair of balanced mixers. LO to the mixers is supplied to the two mixers in the two polarizations through a 4-way splitter. The custom-design wideband quadrature hybrid splitter uses a septum with milled slots, and was qualified for amplitude and phase balance on a VNA. Following successful testing, a production quantity of 50 was made. To allow good integration and tight LO phase match, a 4-way splitter was machined in a split-block design that mates directly to the mixers on the quadrature hybrid.

Measurements of phase and amplitude matching of an ensemble commercial broadband solid-state mixers were made to confirm their suitability and enable selection of matching pairs. Commercial strip-line hybrids are used to combine the IF signals. One IF has a delay adjuster inserted to optimize phase balance, and both IFs have fixed pads with attenuations chosen to optimize amplitude balance.

A complete prototype with dual-circular polarization has been tested in the lab. Measured noise for the receiver, including the OMT and polarizer varies between ~45 and ~70 K. Typically, sideband separation is < 10 dB, but at some frequencies drops to 6 dB. On-the-sky tests were conducted with CARMA, and for line observations the improvement in sensitivity relative to the DSB SIS receivers was ~60%. With dual polarization this will yield a total sensitivity increase of ~2.3.

9914-68, Session PTue1

Development of a new tri-chroic antenna coupled bolometer for measurements of the polarization of the cosmic microwave background and foregrounds in a space environment

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We present the development of a tri-chroic antenna coupled transition edge sensor (TES) bolometer optimized for precision measurements of the polarization of the Cosmic Microwave Background (CMB) and galactic foreground in space environment. These devices employ a polarization sensitive broadband self-complementary sinuous antenna to feed on-chip band defining filters before delivering the power to load resistors coupled to a TES on a released bolometer island. They were originally developed by UC Berkeley for POLARBEAR-2 and SPT-3G and are now being considered as a candidate detector for the LiteBIRD mission, which is designed to measure B-modes from cosmic inflation and to robustly characterize the cosmic foreground from a satellite platform. We present the status of a prototype detector, which will have bands centered on 100, 145, 190 GHz with a fractional bandwidths of 23%, 30%, and 30% respectively. In addition, we present work on tailoring noise properties of these devices to meet the specifications of the experiment by reducing the Tc to 180 mK and thermal conductance of the bolometers to ~10 pW/K in all three bands.

9914-67, Session PTue2

Results of using permanent magnets to suppress Josephson noise in the KAPPa SIS receiver

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We present the results of an investigation with the Kilopixel Array Pathfinder project (KAPPa) instrument. The KAPPa instrument is a THz heterodyne receiver using a Superconducting-Insolating-Superconducting (SIS) mixer that requires a magnetic field to improve performance. The KAPPa instrument can house an electromagnet that can be tuned to optimize the applied field, but it is also capable of accommodating a permanent magnet that applies a fixed field. Our permanent magnet design uses off-the-shelf neodymium permanent magnets and then reshapes the magnetic field using machinable iron concentrators. These concentrators allow the use of an unmachined permanent magnet in the back of the detector block while two small posts provide the required magnetic field across the SIS junction in the detector cavity. The KAPPa test instrument is uniquely suited to compare the permanent magnet and electromagnet receiver performance. The current work includes our design of a 'U' shaped permanent magnet, the testing and calibration procedure for the permanent magnet, and the overall results of the performance comparison between the electromagnet and the permanent magnet counterpart.

SIS mixers in THz heterodyne receivers allow for the down-conversion of high frequency signals (RF) to lower frequency signals (IF) that can be transmitted and analyzed by commercially available components. Efficient down-conversion requires the suppression of Josephson Noise, or Cooper pairs tunneling across the SIS junction, by biasing the junction with a magnetic field. Electromagnets allow for precise tuning of the bias field but are too large and consume too much power to be used in future, densely-packed SIS array receivers. Our strategy to solve the issue of power consumption and packing density for future THz arrays is to replace a tunable electromagnet with an off-the-shelf fixed permanent magnet to create the required magnetic field.

The KAPPa instrument was designed to house either an electromagnet or a permanent magnet. The magnet flexibility allows for the electromagnet and permanent magnets to be installed interchangeably from the backside of KAPPa instrument's detector block without the need to open the detector block and disturb the SIS device or supporting electronics. This feature provides a direct comparison of the same system's performance and an unambiguous test-bed for different magnetic field biasing techniques.

We present results for the KAPPa instrument over the dynamic range of the electromagnet coil tuning compared to the performance with the fixed field strength of the permanent magnet. Our methods for accounting for the hysteretic nature of the magnetic field strength for the optimal suppression of Josephson Noise for both systems are discussed.

Despite not machining our magnets, there is considerable room for changing field strength through magnet selection due to the variety of magnets available and the flexibility of the KAPPa permanent magnet platform. We present techniques for a lab bench measurement of the electromagnet and permanent field strengths. Additionally, we outline our process for selecting permanent magnets that will provide a magnetic field most similar to that of the optimal electromagnet tuning.

9914-69, Session PTue2

Band-1 receiver front-end cartridges for Atacama Large Millimeter/submillimeter Array (ALMA): design and development toward production

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The ALMA Band-1 receiver front-end prototype cold and warm cartridge assemblies, including the system and key components for ALMA Band-1 receivers have been developed and two sets of prototype cartridge were fully tested based on the initial development presented in [1] – [3]. Based on the cryogenically cooled broadband low-noise amplifiers provided by NRAO and the cascode MHEMT mixers developed in ASIAA, the receiver noise temperature can be as low as 15 – 28K for pol-0 and 17 – 34K for pol-1. Other key testing items are also measured. The receiver beam pattern is measured, the results is well fit to the simulation and design. The pointing error extracted from the measured beam pattern indicates the error is 0.1 degree along azimuth and 0.15 degree along elevation, which is well fit to the specification (smaller than 0.4 degree). The power compression is measured, with 380 -436K hot load the compression is less than 4%, which fit to the specification of 5% with 373K input thermal load. The image band suppression is higher than 30 dB typically and the worst case is higher than 10 dB for 34GHz RF signal and 38GHz LO signal, which is all higher than 7 dB required specification. The cross talk between orthogonal polarization is 37 dB based on present prototype LO. The amplitude stability is below 2.0 x 10-7 , which is fit to the specification of 4.0 x 10-7

for timescales in the range of 0.05 s ≤ T ≤ 100 s. The signal path phase stability measured is smaller than 10fs, which is smaller than 22 fs for Long term (delay drift) 20 s ≤ T < 300 sec. The IF output phase variation is smaller than 2.5° rms, and the specification is less than 4.5° rms. The measured IF output power level is -28dBm with 300K input load. The measured IF output power flatness is less than 6 dB for 2GHz window, and 1dB for 31MHz window. All the above items are well fit to the specifications. At the moment of abstract submission, two sets of prototype cartridges have been successfully testes and the other two sets are under assembling, target to be tested in spring 2016 to collect more performance data. The first batch of prototype cartridges will be installed on site for further commissioning before the end of 2016.

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9914-70, Session PTue2

Quantum-limited parametric amplifiers for coherent detection and the readout of superconducting detector arrays

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Quantum-limited parametric amplifiers are promising for readout of large superconducting detector arrays, as well as coherent detection and spectroscopy of astronomical signals. The physics of parametric amplifiers based on superconducting kinetic inductance thin films and Josephson junctions is explored. We provide new insights into four-wave mixing and analyze the effects on amplifier noise performance due to heating, loss, and phase fluctuations. We also illustrate constraints on designing amplifiers using three-wave mixing. We discuss experimental progress toward realizing an amplifier with quantum-limited noise performance, high gain-bandwidth, and large dynamic range. Prospects for readout of large arrays of superconducting detectors, as well as detailed single pixel studies, with quantum-limited amplifiers is discussed. We also explore the possibility of using these amplifiers for coherent detection of astronomical signals.

9914-71, Session PTue2

Development of the new multi-beam 100 GHz band SIS receiver FOREST for the Nobeyama 45-m Telescope

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We report the development of the new 4-beam, 2-polarization, 2-sideband, 100 GHz band SIS receiver "FOREST" (FOur beam REceiver System on the 45-m Telescope) and the results from commissioning and observations on the Nobeyama 45-m Telescope operated by Nobeyama Radio Observatory, a branch of National Astronomical Observatory of Japan. FOREST aims to add new capabilities of large-area mapping and simultaneous multi-line observation at 80 - 116 GHz band to the Nobeyama 45-m Telescope, which is one of the largest millimeter radio telescopes in the world.

The configuration of the four beams is a quadrate of 2 x 2 with the separation between adjacent beams of ~ 50". Beam size of each beam is ~ 15" at 115 GHz. Receiver noise temperature is as low as that of ALMA receivers, so that mapping speed is more than four times as high as that of the other 100 GHz band receivers on the 45-m Telescope. The IF bandwidth is 8 GHz (4 - 12 GHz) realizing simultaneous 12CO, 13CO, and C18O J=1-0 observations. Cooled components inside of cryostat are modularized per beam that includes one corrugated horn, one ortho-mode transducer, two sideband-separating SIS mixers (2SB mixers), two IF quadrature hybrids, four IF isolators, and four CLNAs. IF signals from the cryostat are processed by the room temperature IF system, and then passed to spectrometers.

We have installed the FOREST receiver into the Nobeyama 45-m Telescope, evaluated its performance, and made large area mapping observations. Beam pattern is measured by observing SiO masers, and we obtain beam separations of ~ 50" and beam sizes of ~ 20" at 86 GHz, which are consistent with the optics design. The system noise temperature including atmosphere is ~ 200 K, which is slightly higher than we expected. This is mainly because the SIS mixers are not optimized for such wide IF bandwidth. We are updating the design of SIS junctions and evaluating SIS mixers in laboratory, and we obtain a good candidate that shows DSB receiver noise temperature of ~ 30K at 4 - 12 GHz IF band. We will replace present SIS mixers to new ones next summer. Although FOREST shows an insufficient performance at this moment, its mapping capability, especially with the J=1-0 transitions of 12CO, 13CO, and C18O, is spectacular. We simultaneously achieved rms noise levels of 0.8 K, 0.4 K and 0.4 K at 1 km/s velocity resolution over the 1 deg x 1 deg area with a 5-hour observation for 12CO, 13CO and C18O J=1-0 transitions, respectively. This shows that the mapping efficiency is more than six times higher than that of the previous 25-beam SIS receiver, BEARS.

The FOREST receiver is used for the legacy projects of Nobeyama Radio Observatory, surveying nearby star-forming regions, nearby galaxies ("COMING": CO Multiline Imaging of Nearby Galaxies), and the Galactic plane ("FUGIN" = the Japanese Wind God: FOREST Ultra-wide Galactic plane survey In Nobeyama). Studies based on these surveys are on-going.

9914-72, Session PTue2

Extremely low noise UHF-band amplifier for square kilometer array

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I. INTRODUCTION

In radio astronomy scientists always demand state-of-the art low noise and wideband receivers. With technology advancing and design tools improving, RF engineers can speed up the design cycle and realize the optimal design and ultimate best receiver performance. The Square Kilometer Array (SKA) project is an international effort to build the world's largest radio telescope, with a square kilometer of signal collecting area. The SKA will be the most powerful, sensitive and largest radio telescope ever constructed. Low noise amplifiers dominate the receiver's sensitivity. Most of low noise amplifiers published by far is operating above 1 GHz. A UHF-band cryogenic low noise amplifier was developed for SKA-mid telescope band-1 receiver with a record low noise temperature of 1.5 K and wide bandwidth from 350 to 1100 MHz.

II. DESIGN

It is a challenge to RF engineers to design cryogenic low noise amplifiers with a compact size and low power dissipation at the frequency of 350 MHz and wideband ratio (3:1). As the frequency band moves down to below 1000 MHz, The LNA design needs higher component values, and the circuits get larger in size. MMIC foundry processing has limitations on the fabrication of large value inductors and capacitors. Larger component values have a larger footprint on wafer and larger substrate loss. The large value components fabricated on wafer would compromise Q-factors. Hybrid circuit configuration is not subject to these limitations and is best adapted for a low noise design in the low frequency range. Discrete passive components with high-Q and large values can be selected to integrate with the best low noise transistors to optimize the LNA performance. The cryogenic LNA design for radio astronomy telescope comprises at least 8 parameters, such as low noise temperature, good S11 and S22, high gain, gain flatness, gain stability, gain compression, and unconditional stability beyond the entire operational frequency range. A considerable challenge in LNA design is to simultaneously achieve low noise temperature and good S11. They have complicated correlation and do not always work in each other's favor. Hybrid circuitry has flexibility on circuit layout and component placement. This facilitates minimizing the electromagnetic coupling and interference among the components, which can improve the stability, and reduce the noise from the unwanted feedback in circuit. InP HEMTs exhibit very low noise, high gain, and excellent performance especially at cryogenic temperature. For operating at this very low frequency, the transistors with large gate width and moderate gate length are preferred.

III. LNA PERFORMANCE

A UHF-band cryogenic LNA has been developed and fully tested at cryogenic temperature of 15 K. The cold attenuator method was used to measure the noise temperature and gain of the LNA in cryostat. The LNA was completely tested with 50 Ohm, open and short terminations at the LNA input port to confirm that the LNA was unconditionally stable at cryogenic operation. The LNA achieved an extremely low noise temperature of 1.5 K. The return losses (S11 & S22) were measured ≤ -12 dB at 15 K from 350 to 1100 MHz. The low S11 is preferred for improving the system efficiency and reducing the standing wave between feed and LNA. Given the good S11, this LNA doesn't need an isolator between OMT and LNA input port. Consequently, the receiver can achieve lower noise temperature than the one using an isolator.

9914-73, Session PTue2

Strategies on solar observation of Atacama Large Millimeter/submillimeter Array (ALMA) band-1 receiver

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ALMA covering 35-950 GHz is the existing largest telescope array in the world. Among the 10 receiver bands, Band 1, which covers 35-50 GHz, is the lowest. For solar observation, which is identified as one of the main scientific goals of ALMA, a solar filter with 6-12 dB attenuation is already installed for the other bands. It is equipped with Amplitude Calibration Device (ACD) located between the secondary and the cryostat in the ALMA receiver cabin. However, there are at least two drawbacks when it is applied to Band 1. First, the current solar filter is only 94mm in diameter, and with current Band 1 receiver layout, the beam size is 52mm at the position of the solar filter when observing at 35 GHz. Spillover contributes high noise level in the final data. Second, the solar filter degrades the signal-to-noise ratio due to high attenuation. To overcome this problem, strategies for direct observation toward the Sun are investigated. At millimeter regime, the radiation comes mainly from the chromosphere with brightness temperature of 6000 to 10000 K, it is more than 15 dB stronger in power compared with room temperature load. For active regions, another 15 dB margin is needed. To reduce the system gain, to minimize the impact on noise performance, and to maintain the power compression budget, we thus investigate the de-tuning biasing technique for the RF amplifiers in the system. In current Band 1 system, the cryogenic and room temperature amplifiers are multi-stage HEMT-based amplifiers. The biasing points of transistor in the middle (typically the third stage and the fourth stage) are de-tuned. Preliminary testing at room temperature shows de-tuning one stage can reduce 10 dB gain without degradation in output power compression level. Further gain reducing is possible with de-tuning fourth stage without hurting power compression level. Impact of the noise performance of the amplifier is little with one stage de-tuned. Changing of input/output return loss is also minimal. The total system gain can be fined-tuned by the following tunable attenuator to comply ALMA output power level requirement. With the strategies, solar observation with HEMT-based receiver shows its superior to SIS-mixer receiver for little degradation in system noise performance. System level testing will be performed in early 2016.

9914-74, Session PTue2

The 7 beams S-band cryogenic receiver for the Sardinia Radio Telescope primary focus: status of project

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The Sardinia Radio Telescope (SRT) is a general purpose fully steerable 64-m diameter radio telescope capable of operating whit high efficiency from 300 MHz up to 115 GHz. The SRT optical design is based on a classic symmetrical Gregorian configuration where both primary and secondary surfaces are shaped in order to remove the stationary wave bouncing between the two mirrors, improving consequently the antenna efficiency. The main reflector consists of a back up structure (bus) which supports the quasi-parabolic active surface. The primary reflector is composed by 1008 aluminum panels. The sub-reflector consists of 49 aluminum panels and along with the prime focus positioner and the associated instrumentation, it's supported by the quadrupod structure connected to the bus. One of the peculiar characteristics of SRT is the availability of three different focal positions, to operate in different frequency ranges: Primary (F1), Gregorian

(F2) and Beam-Wave Guide (F3), with F/D ratio and frequency ranges respectively of: 0.33 (0.3-20 GHz), 2.35 (7.5-115 GHz), and 1.37 & 2.84 (1.4- 35 GHz). The primary focus has a feed edge illumination of 74°, while for the Gregorian focus the half aperture angle is 12°. At this moment on SRT there are three receivers installed, one for each focus. In the primary focus there is a dual frequency LP receiver, which operates simultaneously in both bands P (0.305-0.410 GHz) and L (1.3-1.8 GHz). In the BWG focus there is a mono-feed C-Band receiver (5.7-7.7 GHz). In the Gregorian focus there is a multi beam K-band receiver (18-26,5 GHz). For the second generation of the receiver for the ST, the Observatory of Cagliari (INAF-OAC) is designing a superhetoryne cryogenic array receiver with seven pixel and dual polarization, operating at S-band, 3.0-4.5 GHz. This new instrument will offer large science capabilities forpulsar observations and mapping of radio sources. The main specification of the receiver are as follow:

RF (Radio Frequency) Band: 3.0-4.5 GHz;

Size of the array: seven pixel;

Polarization: two linear polarization for each pixel;

IF (Intermediate Frequency) Band: 0.1-1.6 GHz;

Noise Temperature: < 15 Kelvin for each pixel;

The RF signal path is completely cooled down at 20 Kelvin. It consist of a simple broadband circular feed, a double ridged orthomode transducer (OMT) that divide the signal into the horizontal and vertical polarization. Finally, each polarization is amplified with a commercial low noise amplifier (LNA). The RF chain is repeated identically seven time because the finally configuration of the Focal Plane Array is composed by seven beams. The design of the waveguide passive components, like feed and OMT, were constrained by the available space along the optical axis direction, (1 m) inside the focal cabin of the telescope.

In this paper, we describe the new architecture of the 7-Beams S-band cryogenic receiver, the final electromagnetic simulations of the overall front end RF chain, the thermal design and the final measurement of the down conversion section.

9914-75, Session PTue2

The control system and the new cryogenics of the 3 mm band SIS receiver for the Sardinia Radio Telescope

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The Sardinia Radio Telescope (SRT), a challenging scientific project of the Italian National Institute for Astrophysics (INAF), is a new general purpose fully steerable 64 m diameter radiotelescope designed to operate with high efficiency across the 0.3-116 GHz frequency range. The technical and scientific commissioning of the telescope has recently been completed and a call for proposal for an early science program released.

We present the status of development of a 3 mm band cryogenic receiver, one of the new Front-Ends planned for installation in SRT, which will join the already commissioned telescope instrumentation (P-, L-, C- and K-band receivers). The instrument is an old-generation receiver designed and built at IRAM (Institut de RadioAstronomie Millimétrique) which was deployed at the Plateau de Bure Interferometer until 2006. Following its decommissioning, it was purchased from INAF with the goal of testing the performance of the active surface of SRT at its highest operational frequencies of approximately 100 GHz. In particular, the receiver will cover the 84-116 GHz frequency range and will be installed at the secondary (Gregorian) focus of SRT. The Front-End is based on a backshort-tuned Single Side Band (SSB) SIS (Superconductor-Insulator-Superconductor) mixer which was cryogenically cooled at 4 K by thermalizing it to a liquid helium vessel located inside a three-stage cryostat, where a CTI 350CP cold head provided the ≈20 K and ≈80 K cooling stages.

In order to allow integration of the receiver in SRT, three important modifications were made to the original design: a) to the cryogenics; b) to the local oscillator; c) to the control system.

a) We changed the receiver liquid helium cryogenics and adopted a cold head from Advanced Research Systems (ARS, model DE-204SF) which is mechanically compatible with the pre-existing CTI350CP model and can be mounted on the cryostat (from Infrared Lab). The ARS cold-head has two cryogenic stages, one at ≈20K (delivering 8 W of cooling power) the other ≈4 K (delivering 0.2W of cooling power), thus allowing a liquid helium-free solution, which much facilitate the receiver maintenance and is compatible with the telescope operation. The choice of this cold head imposed a change both internal and external of this receiver;

b) Rather than using the traditional Gunn-based local oscillator employed at IRAM for pumping the SIS mixer, we utilize an electronically tuned Local Oscillator (LO) based on an Active Multiplied Chain (AMC) and Power Amplifier (PA), developed at NRAO (National Radio Astronomy Observatory) for the ALMA (Atacama Large Millimeter Array) project;

c) The control system is based on a single-board computer from Raspberry, on microcontrollers from Arduino and on a Python program for communication between the receiver and the SRT antenna control software, which remotely controls the backshort-tuned SIS mixer, the receiver calibration system and the local oscillator.

In addition to a detailed description of the points in a), b), c) above, we will present the receiver laboratory test results and comparison with expected performance.

9914-76, Session PTue2

Next generation receivers for the submillimeter array

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The Submillimeter Array (SMA) is an 8 element mm/sub-mm interferometer, operated on the summit of Mauna Kea by SAO and ASIAA. After 11 years of operation, the time has come for an overhaul of the array's cryogenics, receivers and other systems in order to enhance the science capabilities of the array.

Currently the SMA can simultaneously operate two DSB, single polarization receivers, with 2 GHz of IF bandwidth per receiver, or 4 GHz bandwidth for a single receiver. Ongoing upgrades will increase the bandwidth to 2x 8GHz DSB. Either the 200 (200–245 GHz) or 300 (260–350 GHz) receiver can be used on one polarization, while either the 240 (198–282 GHz) or 400 (330–420 GHz) receiver is used on the other. This allows either dual frequency observing on orthogonal polarizations or dual polarization observing within the overlap frequency ranges of orthogonal receivers.

The next generation receiver for the SMA features a new pulse-tube cooled cryostat, which houses cooled receiver selection optics and dual polarization receiver cartridges at 230 GHz and 345 GHz. The selection optics will allow dual polarization observing with either receiver, single polarization/dual frequency observing using a wire grid and one channel of both receivers, or dual polarization/dual frequency observing using a dichroic plate.

Both receiver cartridges will use a single dual polarization feedhorn feeding an orthomode transducer. The use of a single feedhorn will simplify the alignment of the beams for each polarization, while the use of identical mixers in a single receiver assembly for both polarizations should reduce gain fluctuations between the two polarizations.The two wideband receivers are powered by two Local Oscillator modules continuously tunable between 210-270 GHz and 280-360 GHz. These LO signals will be brought into the cryostat in waveguide, and coupled via waveguide directional couplers. The SIS mixers will be developments of the existing

SMA wideband SIS mixers, each providing at least 14 GHz (4-18 GHz) of DSB IF bandwidth.

Given that the new receivers will provide a total instantaneous bandwidth of 4 x 14 = 56 GHz, transporting this IF bandwidth to the correlator will require a number of changes to the SMA signal transport scheme, with the deployment of a 1550 nm WDM system over the existing optical-fibers. The SMA is committed to further develop the ultra-wideband digital backend (SWARM), which it pioneers, to handle the bandwidth of the new receiver systems.

The simplification of the receiver optics and use of a smaller cryostat for the main receiver bands will allow space in the receiver cabin for a "guest receiver" position that will be able to accommodate a variety of interchangeable receiver systems that could be developed for specific large scale observing programs or to provide new observing capabilities. Examples of possible guest receivers include high frequency receivers for the 650 or 800 GHz bands, dual frequency receivers targeting the 492 GHz and 806 GHz ionized carbon lines and small multibeam array receivers.

9914-77, Session PTue2

Status of the radio receiver system of the Sardina Radio Telescope

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The Sardinia Radio Telescope (SRT, www.srt.inaf.it) is a general purpose fully steerable 64-m diameter antenna, capable of operating at high efficiency from 300 MHz up to 115 GHz. The SRT optical design is based on a classic Gregorian configuration, where both primary (M1) and secondary (M2) reflector surfaces are shaped in order to remove the stationary standing wave bouncing between the two mirrorsThe main reflector consists of a back-up structure which supports the quasi-parabolic active surface. The M1 and M2 are made respectively of 1008 and 49 aluminum panels, are and supported by a back-up and a quadripod structure. SRT has been designed to observe from six focal positions and to be equipped with up to twenty seventeen receivers: Primary focus (F1), Gregorian focus (F2) and Beam-Wave Guide foci (F3-F5 and F4-F6), with focal length to diameter ratio (F/D) and frequency ranges respectively equal to 0.33 (0.3-20 GHz), 2.35 (7.5-115 GHz), and 1.37 & 2.84 (1.4- 35 GHz). At the moment on SRT there are installed 3 radio receivers, one for each focus. A dual linear polarization coaxial receiver, that covers two frequency bands, the P band (305-410 MHz) and the L band (1.3-1.8 GHz) is arranged in the primary foci (F1). A double circular polarization mono-feed, that covers the High C band (5.7-7.7 GHz) is installed in the beam waveguide (BWG) foci (F3). Finally, a multi-beam (seven beams) double circular polarization K band Receiver (18-26.5 GHz) is installed in the Gregorian foci (F2). The typical schematic diagram of the receiver for the antenna is a superheterodyne configuration. The radiofrequency (RF) reflected from the mirrors is coupled with the feed antenna and then amplified with by a cryogenic LNA (low noise amplifier), mixed with a strong amplitude local oscillator in order to generate the intermediate frequency band proportional to the RF signal. The K and C band are based on a superheterodyne configuration, instead the LP band, due to its low RF band, is transported inside the standard intermediate frequency range of the system (IF range: 0.1-2.1 GHz) and doesn't has because it is not provided of a down convertion section. The RF chain between the three receivers are quite different and we will show these differences into this paper. Another fundamental aspect of our receivers is that they operate at cryogenic temperature (typically below 20 Kelvin) to improve the total noise temperature noise of the system. In conclusion in this paper, we describe each single configuration of the receivers, showing the most important performances like system temperature (Tsys), half power beam width (HPBW), stability. In the last part of the document we will anticipate the second generation of the radio receivers for the SRT.

9914-78, Session PTue2

Wideband millimeter and submillimeter-wave parametric amplifiers based on kinetic inductance

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We will discuss progress toward superconducting traveling-wave kinetic inductance parametric amplifiers for the millimeter and submillimeter bands. Microwave frequency versions of these amplifiers, which exploit four-wave mixing in an NbTiN coplanar waveguide transmission line, have demonstrated wide band gain and near quantum limited noise at several GHz. Their simple design is easily scalable to higher frequency, potentially allowing for operation up to about 1 THz, close to the gap frequency of NbTiN. Use of a quantum limited, wide band amplifier at the front end of a sub/millimeter band heterodyne receiver would allow for a much wider instantaneous bandwidth than is achievable with SIS mixers.

We have designed and fabricated waveguide-coupled parametric amplifiers for W-band. Integrated matched filters prevent self-oscillations that may result from out of band reflected power. The results of preliminary measurements on these devices will be described.

9914-79, Session PTue2

Traveling wave parametric amplifiers for millimeter wave heterodyne systems

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We are developing superconducting traveling wave parametric amplifiers for millimeter waves to act as front-end low noise amplifiers for spectroscopy and interferometry applications. We have fabricated W-band amplifiers as NbTiN CPW lines on Silicon substrates with integrated waveguide probes that couple power between split-block waveguide feeds. This design draws on our teams success with microwave frequency amplifiers, but with appropriate modifications for high-frequency operation. We will describe this design and comment on on-going cryogenic tests of noise performance and spectral features performed with a VNA test-bed. In principle, these amplifiers can operate at the quantum noise limit, which could provide substantial sensitivity benefits if used in conjunction with traditional SIS heterodyne systems.

9914-80, Session PTue2

New instrumentation for the 1.2m Southern Millimeter Wave Telescope (SMWT)

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Here we describe the upgrade of the Southern 1.2?m mm? Wave Telescope. The telescope was relocated from Cerro Tololo to Santigo (Chile) allowing for aesier use of the facility by our students and faculties. To compensate for the atmospheric opacity of the new site the front/end was upgraded to

include a sideband separation system. This reduces the noise contribution of the atmosphere by a factor of two. The new LO system and receivers are designed to cover an extended frequency range from 85 to 116 GHz. The receiver is based on low noise amplifier using HEMT technology and two sub-harmonic Schottky mixers for down conversion. The complete receiver is cooled to 80 K by liquid nitrogen. The old back-end based on a filter bank was replaced by a new digital spectrometer, based on the Reconfigurable Open Architecture Computing Hardware (ROACH). This new back-end increases the spectral resolution by a factor of 4 and incorporates digital calibration of the sideband rejection mixer, achieving values of rejection larger than 30 dB across the whole band. Future plans for the instruments include capabilities for simultaneous observations of the 12CO, 13CO and C18O lines. The new telescope control system is under development and the complete system will start scientific observation on 2016/2.

9914-17, Session 4

GISMO-2: a two-color millimeter bolometer camera for the JCMT

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The GISMO 2 mm bolometer camera at the IRAM 30m telescope has been available to the astronomical community for many years. GISMO provides observational capabilities across a wide range of astronomical targets, including observations of galactic dust and free-free emission, the characterization of the SEDs of nearby galaxies, detecting dusty galaxies at high redshifts, and measurements of the Sunyaev–Zel'dovich decrement in the Cosmic Microwave Background Radiation, which traces the evolution of massive galaxy clusters throughout the history of the universe. The 2 mm band is well suited to trace the first dusty galaxies in the universe, since their redshifted SEDs peak close to GISMO's observing frequency, whereas the medium redshift galaxy foreground is almost invisible in this band. This effect makes GISMO's deep field observations a valuable complement, rather than a redundancy, to the HERSCHEL far-infrared and sub-mm surveys.

The GISMO-2 camera, which will enhance GISMO's observational capabilities significantly by utilizing larger detector arrays in two bands at 1.2mm and 2 mm, is planned to start operations at the JCMT in late 2016. A warm dichroic will enable simultaneous observations with SCUBA-2, which will allow for synchronized 4 color observations between 0.45 mm and 2 mm. This capability will not only allow to obtain simultaneous multi-color images of astronomical objects/fields, but will also enable better calibration.

We will describe the expected performance of GISMO-2 at the JCMT and summarize the scientific capabilities enabled by its simultaneous operation together with SCUBA-2.

9914-18, Session 4

Instrumental performance and results from testing of the BLAST-TNG receiver, submillimeter optics, and MKID detector arrays

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Polarized thermal emission from interstellar dust grains can be used to map magnetic fields in star forming molecular clouds and the diffuse ISM. The Balloon-borne Large Aperture Submillimeter Telescope for Polarimetry (BLASTPol) flew from Antarctica in 2010 and 2012 and has produced degree scale polarization maps of several nearby molecular clouds with arcminute resolution. The success of BLASTPol has motivated a next-generation instrument, BLAST-TNG, which will use ~3000 linear polarization sensitive Microwave Kinetic Inductance Detectors (MKIDs) combined with a 2.5 m diameter carbon fiber primary mirror to make diffraction limited observations at 250, 350, and 500 microns. With 16 times the mapping speed of BLASTPol, sub-arcminute resolution, and a longer flight time, BLAST-TNG will be able to examine nearby molecular clouds and the diffuse galactic dust polarization spectrum in unprecedented detail. The cryogenic receiver and detector arrays have been integrated and are undergoing extensive testing prior to deployment to establish the optical and polarization characteristics of the instrument. Progress on BLAST-TNG offers insight into the effectiveness of kilopixel

MKID arrays for application in submillimeter astronomy. BLAST-TNG is scheduled to fly from Antarctica in December 2016 for 28 days and will be the first balloon-borne telescope to offer a quarter of the flight for "shared risk" observing by the community.

9914-19, Session 4

An upgraded SCUBA-2 for JCMT

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SCUBA-2 is a state of the art wide field camera for the JCMT. SCUBA-2 has been fully operational for over 4 years, producing a wide range of science results, including a unique series of survey programs. A new large survey programme has just commenced and for the first time, we offer polarisation sensitive measurements using POL-2, the polarimeter ancillary instrument. We present plans and discuss the science case for upgrading SCUBA-2 with new detector arrays, that will keep SCUBA-2 and the JCMT at the forefront of continuum submillimetre science.

9914-20, Session 4

Detector modules and spectrometers for the TIME-Pilot [CII] intensity mapping experiment

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TIME-Pilot is a new mm-wavelength grating spectrometer array that will study the Epoch of Reionization (the period of time when the first stars and galaxies ionized the intergalactic medium) by mapping the fluctuations of the redshifted 157.7 ?m emission line of singly ionized carbon ([CII]) from redshift z ~ 5.2 to 8.5. As a tracer of star formation, the [CII] power spectrum can provide information on the sources driving reionization and complements 21 cm data (which traces neutral hydrogen in the intergalactic medium). Intensity mapping provides a measure of the aggregate population without the need to resolve and detect faint sources individually. We target a 1 degree by 0.35 arcminute field on the sky and a spectral range of 199-305 GHz, creating a spatial-spectral slab which is 140 Mpc by 0.9 Mpc in x and y by 1230 Mpc in z. With careful removal of intermediate-redshift CO sources, we anticipate a detection of halo-halo clustering in [CII] consistent with current models for star formation history in 240 hours on the JCMT.

TIME-Pilot will use two stacks of 16 parallel-plate waveguide spectrometers (one stack per polarization) with a resolving power R ~ 100 and a spectral range of 183 to 326 GHz. The range is divided into 60 spectral channels, of which 16 at the band edges on each spectrometer serve as water vapor monitors. These monitor channels have a total water vapor sensitivity greater than that in the science band. The diffraction gratings are curved to produce a compact instrument, each focusing the diffracted light onto an output arc sampled by the 60 bolometers. The bolometers are built in 1D buttable dies of 8 or 12 spectral channels x 8 spectrometers and are mated to the spectrometer stacks. Detectors consist of gold micro-mesh absorbers and titanium transition edge sensor (TES) thermistors. The detectors (1920 total) are designed to operate from a 250 mK base temperature in an existing cryostat with a photon-noise-dominated NEP of ~1e-17 W/Hz^1/2. A set of flexible superconducting cables connect the detectors to a time-domain multiplexing SQUID readout system. This talk will give an update on the current TIME-Pilot instrument design and status with a focus on the close-packed modular detector arrays and spectrometers. Results of laboratory tests with prototype detectors and spectrometers will be discussed.

9914-21, Session 4

Performance of backshort-under-grid kilopixel TES arrays for HAWC+

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HAWC+ was selected as the second generation instrument for the Stratospheric Observatory for Infrared Astronomy (SOFIA). It is a far-infrared wide-field camera and polarimeter with general capability for the observatory with deployment anticipated in early 2016. In order to provide high mapping speeds, the camera utilizes kilopixel Backshort Under Grid (BUG) TES-based detector modules, provided by NASA/GSFC. These modules consist of planar 32x40 pixel arrays of close-packed TES bolometers with a separate optical back-termination wafer inserted into the grid. The detector array is bump bonded to a 32x41 pixel time domain multiplexer from NIST/Boulder. The arrays are designed to provide background-limited sensitivity in all of the instrument's five selectable FIR bands (ranging from 53 to 215 ?m). In order to provide for differential polarimetry, the camera employs two separate focal plane arrays, with the final goal of each a mosaic with two modules abutted to produce a nearly-filled 64x40 pixel active area (at this time three of possible four arrays are installed). We present a summary of the detector characterization in the laboratory and discuss the derived performance parameters. These measurements provide the first demonstration of kilopixel BUG arrays.

9914-23, Session 5

Lumped element kinetic inductance detectors for space applications

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Kinetic Inductance Detectors (KIDs) are now routinely used on ground-based telescopes. These large arrays, deployed in formats up to several kilopixels, exhibit state-of-the-art performance at millimeter (e.g. 120-300 GHz, NIKA and NIKA2) and sub-millimeter (e.g. 350-850 GHz, AMKID) wavelengths. KID technology has many distinct advantages compared to bolometers, among which is that the detectors are deposited directly on a solid mono-crystalline substrate. Thus the complications and difficulties associated with micro-machined suspended structures is avoided. These fine structures are necessary in the case of bolometric detectors to realise the extremely low thermal conductivity that must exist between the thermistor/absorber and the thermal bath. Their geometry can have the added advantage of reducing cosmic-ray collisional cross-section. One as-yet unquantified issue with KID technology for space applications has been potential susceptibility to cosmic ray hits. To investigate this we have studied in detail the interaction of ionizing particles (muons, alphas, x-rays) with KID arrays of hundreds of pixels designed for Cosmic Microwave Background observations. We have developed for this purpose a dedicated system of read-out electronics with which we are able to sample at MHz frequencies a number of pixels and thus follow in real time the propagation of a-thermal phonons across the array substrate. We have also set up a dedicated cryostat in which we reproduce typical observing conditions of a space-borne CMB observation. In these conditions we irradiate the KID arrays with alpha particles and X-rays. We confirm that the rate of hits is larger in KIDs compared to bolometers. However, KIDs not only have a much faster response time constant but also are less sensitive to base temperature variations. We conclude that the KID arrays used in this study would behave a factor of ten better than Planck detectors. In addition we have found other ways to further reduce the physical region of the KID array that is affected by a cosmic ray event. We have characterized the influence of the ground plane filling factor and composition in limiting the propagation of the Cooper-pair-breaking phonons over large distances across the substrate, and shown that the effects of cosmic ray hits can be confined to a small region around the position of impact. We will report the details and conclusions from a large number of measurements.

9914-24, Session 5

Dual polarization LEKIDs for millimeter wavelengths

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We discuss the design considerations and the measured performance of arrays of dual-polarization, lumped-element kinetic inductance detectors (LEKIDs) nominally designed for cosmic microwave background studies. The detectors are horn-coupled, and each array element contains two single-polarization LEKIDs, which are made from thin-film aluminum and optimized for a single spectral band centered on 150 GHz. We are developing two array architectures, one based on 160 micron thick silicon wafers and the other based on silicon-on-insulator (SOI) wafers with a 30 micron thick device layer. The SOI architecture promises enhanced performance at the cost of added fabrication complexity, so we are investigating the tradeoffs between these two approaches. Our 20-element test arrays (40 LEKIDs) are characterized with both a linearly-polarized electronic millimeter wave source and a thermal source. We present (i) measurements of the noise-equivalent power and noise-equivalent temperature, (ii) the low-frequency noise properties, and (iii) measurements of the polarization selectivity of these dual-polarization devices.

9914-25, Session 5

A study of novel superconducting material systems for use in microwave kinetic inductance detectors

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We report on the effects of using new superconducting materials in the fabrication of microwave kinetic inductance detectors (MKIDs). The main motivation for this work is to search for a replacement for the TiN superconductors used in the majority of current MKID devices. Although TiN MKIDs have already shown photon counting capabilities with moderate energy resolution, they suffer from spatial non-uniformities in the TiN superconducting critical temperature across a wafer. In large MKID arrays, these variations in critical temperature cause resonators to shift away from their designed frequency, and collisions in frequency space render the resonators unusable by the readout. To counter this shortcoming, we explored superconducting materials that are inherently more uniform than TiN.

To begin testing materials for their potential as MKID superconductors, we developed a simple one layer test mask with a multitude of structures that could test films spanning a wide range of sheet inductance. The test mask could be used to probe a variety of important MKID resonator properties such as critical temperature, internal quality factor, surface impedance uniformity, quasiparticle lifetime, energy resolution, and quantum efficiency. The material we have spent the majority of our time investigating, and the one that currently shows the most promise, is platinum silicide. We measured a critical temperature of 900mK for thin PtSi films, which is in an ideal range for use in adiabatic demagnetization or dilution refrigerators. Resonators structured from PtSi films show high internal quality factors (>150,000) and energy resolution similar to that of TiN (>10). The quantum efficiency is also comparable to that of TiN, but begins to exceed that of TiN for longer wavelengths. Most importantly, we find that the uniformity in surface impedance is about an order of magnitude better in the PtSi films than it is in the standard TiN films.

We examine a few other materials including niobium silicide, tungsten silicide, and osmium using one layer test structures. We then compare the resonators created with these materials and describe the types of instruments and applications most suited for a particular material. For example, most MKIDs benefit from long quasiparticle lifetimes which improve energy resolution, but for higher energy detectors in which a membrane structure is required, it may be more advantageous to have quasiparticle lifetimes be short compared to thermal timescales.

9914-26, Session 5

Photon noise limited performance over an octave of bandwidth of kinetic inductance detectors for sub-millimeter astronomy

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We present the development of background limited kinetic inductance detectors (KIDs) for sub-millimeter (sub-mm) astronomy applications to be used in space based observatories. The sub-mm radiation is coupled to the KID via a leaky wave antenna covering the frequency range from 1.4 to 2.8THz. We have developed a hybrid niobium titanium nitride/aluminium (NbTiN/Al) KID, fabricated on a silicon (Si) substrate, in which the leaky wave antenna and absorbing section of the KID are fabricated on a suspended silicon nitride (SiN) membrane. The radiation is coupled to the leaky wave antenna with a Si lens placed on top of it at a distance of 3?m. We observe photon noise limited performance both in the phase and amplitude readout simultaneously, with a good optical efficiency at a frequency of 1.55THz. The Fourier Transform Spectroscopy (FTS) measurements showing the broadband radiation coupling for an octave of bandwidth, and the beam pattern measurements at 1.55THz are also presented. In summary, we have developed a new fabrication route that assures photon noise limited performance, and a scalable assembly method that provides the 3?m gap space between the antenna and the lens. These developments assure background limited performance with a broad frequency coupling over an octave of bandwidth for sub-mm radiation. Given these results, hybrid NbTiN/Al leaky wave antenna coupled KIDs will enable astronomically usable kilopixel arrays for sub-mm imaging for future space missions.

9914-27, Session 5

Antenna coupled kinetic inductance detectors for multi-band CMB instruments

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To make continued progress in studies of the cosmic microwave background (CMB), multiple telescopes with at least 10^5 polarization sensitive detectors operating at multiple wavelengths will be required. The scientific potential for such an instrument is significant: a Stage-IV CMB experiment will measure the absolute mass of neutrinos to four-sigma, constrain the number of neutrino species at an unprecedented level and rule out (or confirm) the presence of non-interacting sterile neutrino species. It will also extend the search for primordial B-mode polarization, the smoking gun evidence for inflation in the early universe, at a level two orders of magnitude lower than present limits and test a large class of theoretically favored models. However, the technical challenges are daunting: such an instrument will require square meters of focal plane covered in background limited cryogenic detectors, and a dramatic scaling up of existing readout hardware.

A promising technology is the kinetic inductance detectors (KID), which will allow for more robust fabrication and naturally multiplexed readout. We will present an update on the development of a novel KID detector optimized for studies of the CMB. Our design employs titanium-nitride (TiN) lumped element KIDs (LEKIDs) operating at a readout frequency of hundreds of MHz. Broad-band, planar, dual polarization antennas with Si lenses deliver mm-wave radiation to band defining microstrip structures which then deposit power on the inductor of each LEKID. The detectors include a novel broad-band coupling scheme for delivering power from a symmetric Nb microstrip to a single-layer TiN meander located on the ground-plane layer. Prototype designs feature five dual-pol spectral channels covering the telluric windows above 70 GHz.

We will present an overview of the detector design, simulations of the mm-wave and microwave features, and performance estimates based on measured material properties. We will also discuss ongoing progress toward the fabrication of optical devices, including microwave characterization and dark noise measurements of locally fabricated TiN resonators and process verification of test structures that will enable mm-wave coupling.

9914-28, Session 6

BICEP3 performance overview and future prospects for a multi-receiver array

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BICEP3 is a 520-mm aperture compact two-lens refractor designed to observe the polarization of the cosmic microwave background (CMB) at 95 GHz. Its focal plane consists of modularized tiles of antenna-coupled transition edge sensors (TESs), similar to those used in BICEP2 and the Keck Array. The increased per-receiver optical throughput compared to BICEP2/Keck Array, due to both its faster f/1.7 optics and the larger aperture, will more than double the combined mapping speed of the BICEP/Keck program. The BICEP3 receiver was recently upgraded to a full complement of 20 tiles of detectors (2560 TESs), and is now beginning its second year of observation at the South Pole. We report on its current performance and observing plans. Given its high per-receiver throughput while maintaining the advantages of a compact design, BICEP3-class receivers are ideally suited as building blocks for a 3rd-generation CMB experiment, consisting of multiple receivers spanning 35 GHz to 220 GHz with total detector count in the tens of thousands. We present preliminary plans for such an array, including design optimization, frequency coverage, and deployment/observing strategies.

9914-29, Session 6

Second year detectors performance of BICEP3

Howard Hui, California Institute of Technology (United States)

BICEP3 is the newest telescope in the BICEP/ Keck collaboration, started its observation at the South Pole in April 2015. It is a 550mm aperture refractive telescope observing the polarization of the cosmic microwave background at 95GHz at degree-angular scales. We upgraded from 9 detector tiles to fully-populated 20 tiles, 1280 dual-polarization pixels during the austral summer of 2015-16. We will show the focal plane design and detector performance, including near and far-field beam, spectral response, magnetic pickup, optical efficiency and sensitivity of the upgraded BICEP3.

9914-30, Session 6

A report on the in-flight performance of Spider: a sub-orbital mm-wavelength CMB polarimeter

William C. Jones, Princeton Univ. (United States)

We report on the in-flight performance of Spider, a sub-orbital mm-wavelength polarimeter designed to measure the polarization of the Cosmic Microwave Background on angular scales from 20 to 0.5 degrees. Spider has produced polarized surveys covering ~10% of the full sky in the southern Galactic hemisphere at 94 and 150 GHz, with the instrument having the highest instantaneous sensitivity ever achieved at these frequencies. We report on the instrument and in-flight performance of the system, which uses wide format arrays of time-division multiplexed superconducting transition edge sensors.

9914-31, Session 6

Development of 285 GHz feedhorn-coupled TES arrays for the balloon-borne polarimeter SPIDER

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We describe bolometric detector arrays under development for the second flight of the balloon-borne instrument SPIDER. In the 2015 flight, SPIDER made large angular scale measurements of CMB polarization at band centers near 90 GHz and 150 GHz. The second flight will have expanded frequency coverage, including three arrays of feedhorn-coupled TES polarimeters, fabricated at NIST and optimized for detection at 285 GHz in order to characterize polarized dust foregrounds. The silicon-platelet, feed-coupled detector architecture has been used in ground-based instruments SPTpol and ACTPol. Here we describe design changes required to scale up in frequency and optimize for the balloon environment. We present the focal plane design, which consists of a 16x16 array of conical, corrugated feeds with ~5? horn diameter apertures to match the telescope optics. By fabrication and measurement of single horns of this design, we demonstrate near Gaussian-shaped beams with a beam waist that matches the design and < 1% ellipticity in a 30% fractional bandwidth centered on 285 GHz. A feedhorn array couples to a monolithic detector array, fabricated on a 150mm diameter substrate. Each pixel of the array is comprised of a dual-polarization sensitive antenna coupled to two transition edge sensor bolometers, one for each polarization. Each bolometer is operated from a 300mK bath

temperature, has a designed saturation power of 3 pW to take advantage of the low background photon loading, and is read out with a time-division SQUID multiplexer. In addition to the detailed design description, we present the results of a SiN leg-isolated bolometer study used to realize the low thermal conductivity bolometers required for SPIDER.

9914-32, Session 6

In-flight performance of the PILOT balloon borne experiment

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Measuring precisely the faint polarization of the Far-Infrared and sub-millimetre sky is one of the next observational challenges of modern astronomy and cosmology. I will describe the concept and science goals of the PILOT balloon-borne experiment project, dedicated to measuring the linear polarization of the faint interstellar diffuse dust emission in the Far-Infrared in our Galaxy and nearby galaxies. I will present the in-flight performance of the experiment as observed during the successful first flight of PILOT from Timmins, Canada in September 2015.

9914-82, Session PWed1

SHARP: a super-sized 345GHz heterodyne array for JCMT

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As part of the JCMT Future Instrumentation Project, the EAO looks to optimise the premier niche of the facility as the go-to telescope for fast, deep wide-field mapping of the universe at 345GHz (850um). SHARP (Super-HARP) will be designed to provide deep ultra-fast mapping capabilities that takes advantage of the full field-of-view available to the telescope, and an array of 100+ SIS mixers. The preliminary design options will be discussed, as well as the critical science drivers for the project.

9914-81, Session PWed2

Design of corrugated-horn-coupled MKID focal plane for LiteBIRD

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A focal plane based on MKID has been designed for the cosmic microwave background (CMB) polarization observation satellite, LiteBIRD.

The LiteBIRD measures the polarization of the CMB with sigma (r) of 0.001, and explores physics of the inflation before the Big Bang.

The satellite is planned to be launched by JAXA in the 2020s.

The superconducting sensors (TES or MKID) of the focal plane are cooled to a temperature of 100mK and observe 50 GHz - 300 GHz, and make whole sky polarization map with 5 ?K · arcmin.

We are designing and developing a focal plane with broadband corrugated horn array, planar OMT, 180 degree hybrid, bandpass filters, and MKIDs. The focal plane consists of 3 octave bands (55 – 108 GHz, 80 – 160 GHz, 160 – 320 GHz), 10 hexagonal modules. Broadband corrugated horn-array has been directly machined from an Al block and measured to have a good beam shape which is consistent with electromagnetic field simulations in octave bands (120 - 270 GHz, 80 - 160 GHz). The horn array is designed to be low standing-wave, light weight, and electromagnetic shield. The broadband 4 probes ortho-mode transducer (OMT) is fabricated on Si membrane of an SOI wafer. An 180 degree hybrid made with coplanar waveguide (CPW) is used to reduce higher modes of the circular waveguide. Two bandpass filters of each polarization are patterned with Nb microstrip. Al-MKID achieved dark NEP of 2 ? 10^(-18) W / rHz and has been demonstrated to be no degradation after the 10 krad proton irradiation which corresponds to a total dose during 5 years at L2 orbit. We report system design of the focal plane, the sensitivity forecast, and prototype measurements.

9914-84, Session PWed2

Responsivity boosting in FIR TiN LEKIDs using phonon recycling

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To further characterize the cosmic star formation history at high redshifts, a large-area survey by a cryogenic 4-6 meter class telescope with a focal plane populated by tens of thousands of far-infrared detectors is needed. With a primary aperture cooled to 4 Kelvin and equipped with sufficiently sensitive detectors, the sensitivity of such a surveyor would be limited by astrophysical backgrounds. Broadband detector noise equivalent powers (NEPs) on the order of 3e-19 W/sqrt(Hz) are required to be photon noise limited. Kinetic inductance detectors (KIDs) show great promise for a mission such as this because of their intrinsic frequency multiplexability and simple cryogenic amplification requirements.

KIDs are high quality factor superconducting resonators — their superconducting current is carried by Cooper pairs. When photons of sufficient energy are absorbed by KIDs, the Cooper pairs are broken up into individual electrons — quasiparticles. When quasiparticles recombine, they emit phonons which propagate through the substrate and are lost to the low-temperature bath. However, if phonons can be confined to the KID substrate, they can break additional Cooper pairs, thereby increasing responsivity and reducing NEP. We refer to this mechanism as “phonon recycling”.

We present the design and initial characterization data of an array of 96 350 micron phonon-recycling KIDs. Our KID array is fabricated with TiN deposited on a silicon-on-insulator (SOI) wafer, which is a 2 micron thick layer of silicon bonded to a thicker slab of silicon by a thin oxide layer. The backside thick slab is etched away underneath the absorbers so that the detectors are suspended on just the 2 micron membrane. The intent is that quasiparticle recombination phonons are trapped in the thin membrane, thereby increasing their likelihood of being re-absorbed by the KID to break additional Cooper pair and boost responsivity.

9914-86, Session PWed2

Development of octave-band planar ortho-mode transducer with MKID for LiteBIRD

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LiteBIRD is a next-generation satellite mission for measuring the primordial B-modes polarization signals of CMB [1]. We describe a design of octave-band corrugated horn coupled planar ortho-mode transducer (OMT) [2,3] with Microwave Kinetic Inductance Detector (MKID) [4] as a candidate detection technology for LiteBIRD.

In our design, each single pixel contains 90 and 150 GHz two frequency bands, covering the maximum power part of CMB polarization signal. Through a 2.4 mm diameter circular waveguide, polarization signal are coupled to the 4-probe planar OMT structure silicon membrane, below which a backshort structure with quarter wavelength is fabricated by deep reaction-ion etching from the backside of silicon on insulator wafer.

After planar OMT, a broadband coplanar waveguide (CPW) 180-degree hybrid [5] is used to cancel higher modes from circular waveguide. An Al/Ti center strip acts as absorber to absorb higher modes signal and TE11 signal is transmitted to a CPW-to-microstrip (MS) transition structure for connecting MS 5-element Chebyshev diplexer and following MKID. For coupling signal to MKID, the center strip of MKID acts as ground of MS and absorber to generate quasi-particle [6]. For testing, a 4-pixel model is designed, containing 16 MKIDs and 4 dark MKIDs. MKIDs are designed with Nb ground plane and Al/Ti bilayer center strip line to achieve low frequency response and high sensitivity.

The 4-pixel broadband corrugated horn array is fabricated with high accuracy direct machining. Measurement shows that S11 parameter is lower than -10 dB from 80 GHz to 170 GHz and agree well with simulation. After calibration and testing, this prototype will be installed on Nobeyama 45-m telescope.

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9914-88, Session PWed2

Responsivity and noise in TiN/Ti/TiN kinetic inductance detectors

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We are developing TiN/Ti/TiN trilayer and multilayer films for feedhorn-coupled polarization-sensitive kinetic inductance detectors (KID) for the balloon-borne instrument BLAST. We have found unique properties of the TiN/Ti/TiN films in both responsivity and noise that differ significantly from conventional superconductors such as Al. On one hand, TiN/Ti/TiN films exhibit linear frequency response over a wide range of loading power and bath temperature. Interestingly, in TiN films, quasiparticles generated either optically or thermally do not seem to directly combine with each other. This also suggests that the responsivity increases as 1/V when the absorber volume V is reduced. On the other hand, we find that the detector dark noise at low frequency is dominated by inductor noise (or kinetic inductance fluctuations), rather than two-level system (TLS) noise from the capacitors. The inductor noise level does not depend on the microwave power or bath temperature, but only upon the inductor width w as 1/w^2. Combining the 1/V scaling of responsivity and the 1/w^2 scaling of noise level, the noise equivalent power (NEP) scales as w. This suggests that lower NEP can be achieved by reducing the absorber volume while keeping the aspect ratio fixed and the impedance matching condition unchanged. Using absorber narrower than 2-micron wide, detector NEP below 10^-17 W/(Hz)^0.5 at 1 Hz may be achieved.

9914-94, Session PWed2

Fabrication of TiN MKID polarimeter arrays for the BLAST-TNG telescope

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We describe the fabrication and performance of the prototype detector arrays for the Balloon LAunched Submillimeter Telescope – The Next Generation (BLAST-TNG), a suborbital mapping experiment designed to study the role magnetic fields play in star formation and bridge the angular scales between Planck's low resolution all-sky maps and ALMA's ultra-high resolution narrow fields. BLAST-TNG is scheduled to launch from Antarctica in 2016. This experiment will utilize 8 times as many polarization sensitive detectors and will have 16 times greater mapping speed compared to the previous BLAST telescopes.

BLAST-TNG will employ three arrays of microwave kinetic inductance detectors (MKIDs) at 250, 350, and 500 microns. Each spatial pixel consists of a pair of polarization-sensitive resonators fabricated from a Titanium Nitride/Titanium multilayer on a silicon-on-insulator (SOI) wafer. After micromachining each wafer, the device silicon layer of the SOI wafer forms a quarter wavelength backshort optimized for efficient coupling in each band. The TiN/Ti multilayers combine high responsivity, high uniformity, low loss, and a tunable superconducting Tc. The Tc is chosen to balance responsivity with loss from thermal quasiparticles. In single pixel laboratory experiments, the detectors have been shown to be photon noise limited [Hubmayr et al, Applied Physics Letters, 2015] and have excellent polarization sensitivity.

The BLAST-TNG arrays are fabricated on 100 mm Si wafers with a different wafer for each detection band. Each array is read out using several microwave feedlines. Each microwave feedline addresses as many as 600 frequency-multiplexed resonators in 300 spatial pixels, and has been created using a semi-automated layout scheme to make a stepper-

compliant lithography process. The layout and design of the detectors must minimize crosstalk between the resonators as well reduce the number of frequency collisions between resonators. Preliminary results on the array performance will be reported.

9914-95, Session PWed2

Kinetic inductance detectors for far-infrared spectroscopy

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The star formation mechanisms at work in the early universe remain one of the major unsolved problems of modern astrophysics. Many of the luminous galaxies present during the period of peak star formation (between redshifts 1 and 3) were heavily enshrouded in dust, which makes observing their properties difficult at optical wavelengths. However, many spectral lines exist at far-infrared wavelengths that serve as tracers of star formation during that period, in particular fine structure lines of nitrogen, carbon, and oxygen, as well as the carbon monoxide molecule. Using an observation technique known as intensity mapping, it would be possible to observe the total line intensity for a given redshift range even without detecting individual sources. Here, we describe a detector system suitable for a balloon-borne spectroscopic intensity mapping experiment at far-infrared wavelengths. The experiment requires an "integral-field" type spectrograph, with modest spectral resolution (R~100) for each of a number of spatial pixels spanning several octaves in wavelength. The detector system uses lumped-element kinetic inductance detectors (LEKIDs), which have the potential to achieve the high sensitivity, low noise, and high multiplexing factor required for this experiment. We detail the design requirements and considerations, fabrication process, and preliminary performance results for a prototype LEKID array of 1600 pixels. The pixel design is driven by the need for high responsivity, which requires a small physical volume for the LEKID inductor. In order to minimize two-level system noise, the resonators include large-area interdigitated capacitors. High quality factor resonances are required for a large frequency multiplexing factor. Detectors were fabricated using both trilayer TiN/Ti/TiN recipes and thin-film Al, and are operated at base temperatures near 250 mK.

9914-96, Session PWed2

Performance verification of double-slot antenna and elliptical silicon lens for large format KID arrays

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Large format imaging arrays are now a reality due to the recent improvements in detectors performance. In the next decade submm and mm astronomy will benefit enormously from the mapping capability of these instruments followed up with the high spatial and spectral resolution of ALMA (Atacama Large Millimeter/ submm Array). The realization of imaging cameras has been made possible by detectors that combine background limited sensitivity, high optical efficiency and high multiplexing ratio. Microwave Kinetic Inductance Detectors (MKIDs) have shown to satisfy all these requirements, thus becoming a promising candidate for next generation instruments. A MKID consist of a superconducting resonator coupled to a feed-line used for the readout, with radiation coupling, here achieved using antenna coupling. The antenna is placed in the focus of an elliptical lens to increase the filling factor. In this paper we present the design and the optical performance of MKIDs optimized for operation at 850 GHz. The detailed device design takes into account the properties of the substrate material, the Kinetic Inductance of the superconducting metals, the effect of the metal thickness and the exact shape of the Si dielectric lens. We have measured a device consisting of 4 pixels. We have characterized the detector coupling efficiency, antenna-lens frequency response and beam pattern and compared these to theoretical simulations. The optical efficiency has been measured by means of a black body radiator mounted in an ADR cryostat; through the variation of the black body temperature a variable illumination of each pixel (from 0.1 fW to 2 pW) is achieved. The frequency response and beam pattern have been measured in a He3 cryostat directly via the cryostat window and without the use of intermediate optics.

9914-97, Session PWed2

Development of focal plane detectors for GroudBIRD experiment

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Observation of the Cosmic Microwave Background radiation (CMB) polarization provide us knowledge how the Universe was born. The Inflation, accelerated expansion of space-time metric at early stage of the Universe, generated primordial gravitational waves. The primordial gravitational waves can be observed as odd-parity patterns, B-modes, on the CMB polarization map. GroundBIRD a ground based experiment for observing the CMB polarization aims to measure B-modes at large angular scale based on its unique experiment approach. Our instrumental features are high speed rotation scan, cold optics, and Microwave Kinetic Inductance Detector (MKID). Our focal plane consists of corrugated horn coupled MKIDs arrays. We will present its design simulation, hybrid approach of fabrication (usage both mask aligner and stepper), and performance evaluation.

The MKID is one of cutting-edge superconducting detectors. It is easy to readout by frequency domain multiplexing. This is advantage to reduce heat loads from the read-out wires to cold stage. Moreover, fast time response of the MKID is well matched with our scan strategy, the high speed rotation scan to reduce effects of 1/f noise.

Our focal plane consists of seven hexagonal corrugated horn coupled MKID arrays; six hexagon units are for 145 GHz bands (55 pixels/unit), and one unit is for 220 GHz (109 pixels). Each pixel consists of corrugated horn, planner OMT, millimeter wave circuits for transmission of dual-polarization

signals with suppression of crosstalk modes, and two MKIDs for each polarization. The corrugated horn which has the 1/4 lambda wave length structure, makes the beam shape sharp. It has also mode conversion area which is convert form the linear polarization to TE01 mode of the circular waveguide. We make the corrugated horn array and a jig which holds MKIDs array by direct machining.

The OMT consists of two probe antenna pairs on the silicon membrane structure made by deep etching machine. The radio wave is captured by the probe and transport to the MKID through a crossover and a 180 degree hybrid. Between Cross over and hybrid there are two types of impedance transformer, exponential tapered line and second chebyshev transformer. Each resonator of the MKID consists of Niobium films and Aluminum (or Titanium Nitride) films which is sensing parts. the millimeter wave brake the cooper pair in the sensing material and detect the change of MKID resonance parameter.

9914-138, Session PWed2

Fabrication and performance verification of a 961 pixel Kinetic Inductance Detector system for future space borne observatories

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We present the development of a system demonstrator for a future far infrared/sub-millimeter observatory. The system consists of a monolithic detector array of 31 x 31 = 961 antenna coupled microwave kinetic inductance detectors, MKIDs, operating in a 825 – 925 GHz band. The array is read-out using frequency division multiplexing. We use a single pair of coaxial cables, one cryogenic amplifier and a single back-end to read-out al 961 detectors. The back-end consists of a digital/analog readout system capable of reading out up to 4000 MKIDs in a 2 GHz readout bandwidth at a datarate up to 1.2 kHz. The MKID array design is done explicit-ly to achieve a good match with the readout electronics, high pixel yield and high dynamic range.

The performance of the system is tested by placing the detector array in a light tight box and cooling this assembly to 100 mK. A 3-30 K black body radiator, coupled to the central part of the detector array by a 20 mm aperture equipped with band-pass filters, is used to illuminate a part of the array. We find that 85% of the pixels can be used (818 out of 961) and yield an average dark NEP = 4?10-19 W/√Hz, calculated from the measured noise and temperature response of the devices. This sensitivity is not affected by the readout electronics but limited only by the MKID performance.

9914-83, Session PWed3

Improving ALMA’s calibration of atmospheric spectral features: development of high spectral resolution system temperature measurement

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ALMA visibility spectra are calibrated for atmospheric transmission and sky brightness effects by scaling by a system temperature spectrum determined from auto-correlation spectra of the sky and two calibration loads. Up to ALMA Cycle-3 observations, these system temperature spectra have been limited to resolution of around 30 MHz (15.625 MHz channel widths), which whilst sufficient in many cases, insufficiently sample narrower atmospheric emission lines, leading to uncorrected residual errors in higher resolution science spectra. The limited resolution is due to the need for linear autocorrelation response, which is only satisfied in the Baseline correlator’s low resolution “TDM” mode. Extra processing by filter banks in the higher resolution “FDM” mode results in an inability to apply numerical correction for signal quantisation, which is required for linear response. In this paper we present the work of an ALMA Development Study to produce system temperature spectra at full science resolution, including for FDM mode observations. The effects of insufficiently resolved narrow atmospheric lines on science data calibration, and proof of concept demonstrations of measuring system temperature spectra at full science resolution are presented. To achieve meaningful system temperature measurement in FDM mode, without significant hardware and low level software modification in the correlator, we show the results of combining FDM autocorrelations with data from square law detectors in the receiver backends -- a technique which can be implemented in ALMA’s online calibration software. Performance and storage implications of the higher spectral resolution calibration are discussed, as well as downstream implications in the CASA and ALMA Pipeline offline software.

9914-85, Session PWed3

A compact cryogenic calibrator for mm-wave detector characterization

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We describe the construction of a cryogenically-compatible quasioptical source designed to be used for measurements of cryogenic detector arrays operating at millimeter waves. The source is constructed using a carbon-loaded epoxy mixture that is molded into a tiled pyramidal structure. The mold is fabricated using a hardened steel template produced via a wire EDM process. The full angle of the pyramid is 20 degrees, and the measured size of the apex of the pyramid produced by this technique is less than 10 microns. The carbon-loaded epoxy used as the absorbing material has a measured dielectric constant of 6.3+0.47i. A copper backplane is embedded in the epoxy mixture to provide thermalization of the absorbing layer. We present the design and fabrication of this structure. We discuss the thermal design, including the heat capacity and resulting time constant and residual thermal gradients in the structure. Additionally, we discuss the thermal survivability. Finally, we describe the radiometric performance of the structure, including the performance as a function of the angle of incidence.

9914-87, Session PWed3

Analysis of antenna position measurements and weather station network data during the ALMA long baseline campaign of 2015

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In a connected element radio interferometer, the determination of accurate geometrical antenna positions relies on accurate calibration of the dry and wet delay of the atmosphere. For the Atacama Large Millimeter/Submillimeter Array (ALMA), with baseline lengths up to 15 kilometers, the geography of the site forces the height of the more distant antenna pads to be significantly lower than the central array.

Thus, both the ground level meteorological values and the total water column can be quite different between antennas in the extended configurations. During 2015, a network of six additional weather stations was installed to monitor pressure, temperature, relative humidity and wind velocity, in order to test whether inclusion of these parameters could improve the repeatability of antenna position determinations in these configurations. We present an analysis of the data obtained during the long baseline campaign of October through November 2015. The repeatability of antenna position measurements typically degrades as a function of antenna distance. Also, the scatter is more than three times worse in the vertical direction than in the local tangent plane, suggesting that a systematic effect is limiting the measurements. So far we have explored correcting the delay model for deviations from hydrostatic equilibrium in the measured air pressure and separating the partial pressure of water from the total pressure using water vapor radiometer (WVR) data. Correcting for these combined effects still does not provide a good match to the residual position errors in the vertical direction. One hypothesis is that the current model of water vapor may be too simple to fully remove the day-to-day variations in the wet delay. We are now exploring new avenues of improvement, which include recalibrating the baseline measurement datasets using the contemporaneous measurements of the water vapor scale height and temperature lapse rate from the oxygen sounder, and applying more accurate measurements of the sky coupling of the WVRs.

9914-89, Session PWed3

Managing the cryogenic systems of SCUBA-2 for long term operations

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SCUBA-2 has been operational on JCMT producing excellent science for over 4 years. We describe the strategy and methods that we have evolved to keep one of the worlds first “dry dilution refrigerators” and the other cryogenic systems working effectively at the summit of Mauna Kea, keeping the instrument functioning at peak efficiency for extended periods (over 12 months at a time), with minimum downtime. We discuss new plans to reduce day to day operational costs and to add remote management of the gas handling systems, as we look to the future and envisage another ten years of SCUBA-2 science.

9914-91, Session PWed3

The QUIJOTE TGI cryomechanics

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The QUIJOTE (Q-U-I JOint Tenerife) CMB Experiment is operating at the Teide Observatory with the aim of characterizing the polarization of the CMB and other processes of Galactic and extragalactic emission in the frequency range of 10–40GHz and at large and medium angular scales. QUIJOTE consists of two telescopes installed inside a single enclosure, and three instruments, the MFI (multi-frequency 10–30GHz), the TGI (26-36 GHz) and the FGI (37-47 GHz). The first QUIJOTE telescope, together with the MFI instrument, is already operative at the Observatory since November 2012. The second telescope was accepted on site in January 2015.

In this paper we present the TGI cryo-mechanics. The TGI is a 30 pixel polarimeter array with a modular design. This feature permits the assembly and dissasembly of each pixel individually. Each pixel is cooled by three automatic thermal links based in the concept of ALMA cartridge-type cryostat. We designed a crown-like monolithic thermal link with 12 fingers. The thermal link is made of high conductivity oxygen free copper and the clamp belt is made of Teflon©. The cryostat is cooled by a two stage GM cryocooler Leybold COOLPOWER 10 MD. Horns, low noise amplifiers, 20K cold plates and 20K radiation shield are cooled on the 12 K second stage. R22 waveguides, 50K cold plate and 50K radiation shield are cooled on the 50K second stage. To reduce the mechanical vibration an antivibration mount is used as interface between the coldhead and the cryostat and high conductivity oxygen free copper flexibles links are used between the cold head stages and the cold plates. The vacuum vessel, with a cylindrical shape and two diameters, is made of Al6061-T6 to reduce the weight. The cryostat window is a single Mylar© piece of 600mm supported in the 31 holes of the front flange and secured by two PVC© pieces. These PVC© pieces also contains a dry air system to prevent window condensation. Also included is the development of the automatic thermal link, the mechanics of the calibration system as well as the instrument manufacturing, assembly, integration and tests. The TGI instrument is currently undergoing the commissioning phase and will be operating in the second telescope.

9914-93, Session PWed3

Artificial calibration source for ALMA radio interferometer

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The ALMA (Atacama Large Millimeter/submillimeter Array) radio interferometer has some different types of antennas which have a variation of gain and leakages across the primary beam of an individual antenna. We have been developing an artificial calibration source which is used for compensation of individual difference of antennas. In a high-frequency antenna, using astronomical sources to do calibration measurement would be extremely time consuming, whereas with the artificial calibration source becomes a realistic possibility. Photonic techniques are considered to be superior to conventional techniques based on electronic devices in terms of wide bandwidth and high-frequency signals. Conversion from an optical signal to a millimeter/sub-millimeter wave signal is done by a photo-mixer.

We will place a small low-powered millimeter/submillimeter wave source on one of the mountain peaks overlooking ALMA operations site (5000m above sea level).

This will serve several purposes:

(1) to provide a signal for interferometric holography measurements of the antenna surfaces,

(2) to provide a source of known and preferably changeable polarization so we can measure the polarization properties of the antenna/receiver system,

(3) to provide a source with high signal-to-noise ratio to help measure things like coherence, phase stability, switching timing and perhaps stability and sideband ratio.

The artificial calibration source consists a wide-bandwidth noise source, a comb (or a continuous wave) generator, a photo-mixer, and a polarization controller.

The polarization calibration is the most difficult hurdle. Since ALMA has a 0.1 % polarization requirement we certainly need to know what is being produced to this sort of level. The ALMA receivers have two nominal linear polarization channels.

There are two important cases to consider:

(1) the polarization properties of the array of dishes.

(2) the variation of the gains and leakages across the primary beam of an individual antenna, we can make accurate polarization maps of extended sources.

Measurement of the polarization properties of the ALMA receiver system is more complicated than it was assumed. The patterns are quite different for the different antennas. The effect is thought to be due to multi-path propagation in the optics. Although we were expecting the leakage terms, as a function of three parameters (frequency, azimuth offset and elevation offset), to be a function of the position of the source in the primary beam, the assumption was that the pattern would only vary slowly with frequency.

An arrangement of wire grids, including at least one that rotates about an axis perpendicular to the plane of the grid, should be used to produce a pure linear polarization signal at a controlled orientation.

We made a laboratory test with an ALMA receiver. The main purpose of these tests was to confirm that the source produces signals which will be easy to use for calibrating the ALMA system. We will report the performance of the artificial calibration source.

9914-33, Session 7

Polarization sensitive multichroic MKIDs for CMB studies

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We report on the status of an ongoing effort to develop 20-element prototype arrays of horn-coupled, polarization-sensitive microwave kinetic inductance detectors (MKIDs) that are each sensitive to two spectral bands between 130 and 280 GHz. These multi-chroic MKID arrays are tailored for experiments that are designed to simultaneously characterize the polarization properties of both the cosmic microwave background (CMB) and Galactic dust emission. We present the device design and show results from initial laboratory-based characterization measurements. Our device design builds from successful transition edge sensor (TES) bolometer architectures that have been demonstrated to work in instruments on the ACT and SPT telescopes. Therefore, our research program focuses on (i) developing the microstrip-to-CPW coupling between the TES-based on-chip millimeter-wave polarimeter circuit and the distributed MKID and (ii) demonstrating that the performance of theses arrays is competitive with arrays of similar TES-based devices. The 20-element prototype arrays we are building allow us to test the full bandwidth of our ROACH-2-based readout system, which should ultimately allow multiplexing factors of approximately 500. Our prototype array design is directly scalable to 331 elements, and seven of these arrays can be tiled into a 9268 detector array.

9914-34, Session 7

MKID detector development for large scale far-infrared arrays

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We are developing Microwave Kinetic Inductance Detectors (MKIDs) for sub-millimeter through millimeter wave focal planes. Development is focused on improving sensitivity, array size, and multiplexing density to achieve large scale arrays for future far infrared and millimeter wave missions. Current MKID detector design, fabrication and testing efforts are geared toward developing focal planes for BLAST-TNG, which will require approximately 3000 total detectors operating with photon noise sensitivity and polarization sensitivity at 250, 350, and 500 microns. The fundamental design is a feedhorn coupled to two separate MKID resonators with inductors which are orthogonal to each other acting as independent absorbers in the two linear polarizations. Photon noise operation under ~ pW loading has been demonstrated in lab. Various designs of the absorber geometry have been developed to couple the radiation; predictions and lab testing for the optical efficiency, optical and polarization sensitivity, and cross talk for inductors fabricated using various approaches to separate the polarizations will be presented.

Ti/TiN/Ti trilayer and multilayer films offer a high kinetic inductance relative to other materials such as Aluminum and is used as the absorbing element and inductor allowing the resonators to achieve the desired LC frequencies < 1 GHz to meet electronic readout requirements. Additionally the Tc uniformity of these films allows for resonators to behave both uniformly and be close to the designed frequency. BLAST-TNG is being fabricated on 100 mm wafers using two layers of lithography to define the resonators and quarter wave backshorts. The designs are made with consideration toward upgrading the design and process to 150 mm wafers.

We are also exploring the use of TiN for 90 GHz detectors; the ability to reach these longer wavelengths coupled with larger wafer scale fabrication would make the attractive for cosmological application. Preliminary results on detectors at 90 GHz will also be reported.

9914-35, Session 7

Low-volume Al and Al/TiN bilayer LEKIDs for far-infrared astronomy

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Next-generation far-infrared astronomical telescopes, such as the Far Infrared Surveyor that is intended to have a T ~ 4 Kelvin, 4 – 6 meter aperture, require detector NEPs of approximately 3e-19 W/sqrt(Hz) and 3e-20 W/sqrt(Hz) for imaging and spectroscopy, respectively. Such NEPs will match the expected photon background limit of astrophysical sources and hence maximize the capability of the Surveyor for astrophysics. Kinetic inductance detectors (KIDs) are a promising detector technology because they can be multiplexed with minimal cryogenic amplification complexity. Very encouraging progress has been made in KID sensitivities in recent years; however, additional progress remains to be made in sensitivity and in demonstration of many-pixel arrays.

We present the design and characterization of low-volume Al/TiN bilayer and Al-only lumped-element kinetic inductance detectors (LEKIDs) meant to demonstrate NEPs approaching the requirements of applications such as the FIR Surveyor. The LEKIDs are comprised of meandered inductors that serve as radiation absorbers in parallel with interdigitated capacitors, forming high quality factor resonators. Resonance frequencies are in the range of 190 to 360 MHz, with quality factors of 1e4 to 1e5. The interdigitated capacitor architecture is designed to mitigate two-level system noise by lowering electric fields in the substrate (Si) dielectric. Low inductor volumes lead to low NEPs by raising quasiparticles densities, and hence responsivities, with respect to larger volumes. Low volumes are achieved with thin (20 nm), narrow (150 micron) lines. The TiN layer on top of the Al serves as a protective layer, but complicates the superconducting properties compared to Al-only devices. Detector performance properties, including yields, responsivities, NEPs, and noise contributions for 350 um arrays are reported under various optical loading conditions, along with an optical coupling analysis and a comparison of Al/TiN versus Al-only LEKIDs.

9914-36, Session 7

Ultrasensitive kinetic inductance detectors for far-infrared space telescopes

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We are developing ultra-sensitive Kinetic Inductance Detectors (KIDs) suited for the next-generation of far-infrared space instruments and in particular for NASA's notional far-IR surveyor mission. These instruments especially the moderate resolution spectrometers will require either photon counting capability or power detection sensitivity of order 10^-20 W/rt Hz.

We are exploring KIDs made from thin aluminum (10 – 100 nm) and NbTiN (100 nm) films on single-crystal silicon and SOI substrates. We have achieved internal quality factors as high as Qi ~ 7 x 10^6 for 25 nm Al on Si and 2.5 x 10^6 for 100 nm Al on Si resonators. We have also obtained quasi-particle lifetimes of ~ 1 ms for 100 nm Al. Our cryogenic testbed was optimized for ultra low stray radiation, which we confirmed by measurement comparisons. Furthermore, with SOI parallel-plate capacitors we hope to minimize two-level system resonator noise by confining the electric fields inside the crystalline dielectric. Ultimately we will maximize sensitivity by using very small volume kinetic inductors.

We report on dark and optical measurements of single- and double layer resonator KIDs made from these films, and our plans to implement these into optically coupled ultrasensitive KIDs.

9914-37, Session 7

Phonon recycling for low-NEP kinetic inductance detector

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We are developing released Kinetic Inductance Detectors (KIDs) that may boost sensitivity through a process known as phonon recycling. The responsivity of KIDs increases with the life-time of excited quasiparticles,, typically limited to ~100us by decay back into cooper pairs with emissions of a phonon. Our released KIDs on high-purity HF-dipped SOI substrates attempt to "trap" these phonons in a thin 2um films and reflect them back to the KID where they can be re-excite quasiparticles. This should dramatically increase the effective quasiparticle lifetime and thus sensitivity of the device by at least an order of magnitude. Early tests showed such a large responsivity differences between released and un-released KIDs, but there was ambiguity since the release can also alter the optical coupling efficiency. In this study, we address this ambiguity by releasing all devices but altering the perimeter of some devices to change the fraction of phonons that can escape into the surrounding substrate. We will comment on the status of these tests in these talks and discuss measured differences in responsivity as well as detector time constants.

9914-38, Session 8

Next generation sub-millimeter wave focal plane array coupling concepts: an ESA TRP project to develop multichroic focal plane pixels for future CMB polarization experiments

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The main objective of this ESA funded activity is to develop new focal plane coupling array concepts and technologies that optimise the coupling from reflector optics to the large number of detectors required for next generation sub millimetre wave telescopes targeting B Mode detection in the cosmic microwave background (CMB). B mode observations will detect or set an upper bound on the primordial gravitational waves (tensor mode fluctuations) predicted by theories of cosmic inflation. The B mode signal associated with gravitational waves have not yet been detected from the ground or via balloon borne instruments and a space mission may offer the best opportunity to observe these weak inflationary signals.

To reach the sensitivity levels required many thousands of polarisation sensitive detectors are required in the focal plane of a large telescope. This leads to challenges in the optical design of the system. The traditional horn arrays used in CMB missions are heavy and difficult to cool so a new planar focal plane technology is desirable for such a future B mode mission. The development of multichroic operation will allow the reduction in size of the potential focal plane area. In light of these requirements a multichoic planar pixel design was developed as part of a European Space Agency (ESA) TRP programme. After a detailed scientific and technical review of existing technology, the consortium were tasked with designing, manufacturing and the experimentally verifying a prototype multichroic pixel which would be suitable for the large focal plane arrays required to reach the sensitivity levels to detect CMB B modes. The proposed pixel is based on a planar mesh lens focusing incident radiation to detector via a multichoic planar antenna. The mesh lens operates by achieving the appropriate transmission and phase delays across the lens surface using a sub wavelength size metal mesh or grid in a thin dielectric layer. The technology is very robust, and can be used cryogenically as well as in space environments as normal mesh filters.

A number of different planar antenna configurations were investigated including a wideband sinuous antenna and a configuration of slot antennas referred to a seashell antenna. The detector chosen for the prototype design is a CEB bolometer but this coupling concept can also be used with other detector types. For the prototype pixel only dual frequency operation will be demonstrated at 75 and 105 GHz in the w band close to the peak CMB signal. In order to fully verify the operation of the pixel a number of room and cryogenic measurements were planned. The optical behaviour of the mesh lens and antenna are carefully measured along with the spectral response of the antenna coupled detector to allow accurate characterisation for each pixel component.

9914-39, Session 8

Optical characterization and analysis of multi-mode pixels for use in future far-infrared telescopes

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In this paper we present the development and verification of feed horn simulation code based on the mode-matching technique to simulate the electromagnetic performance of waveguide based structures of rectangular cross-section. This code is required to model multi-mode pyramidal horns which may be required for future far infrared (far IR) space missions where wavelengths in the range of 30 to 200 ?m will be analysed. Multi-mode pyramidal horns can be used effectively to couple radiation to sensitive superconducting devices like Kinetic Inductance Detectors (KIDs) or Transition Edge Sensor (TES) detectors. These detectors could be placed in integrating cavities (to further increase the efficiency) with an absorbing layer used to couple to the radiation. The developed code is capable of modelling each of these elements, and so will allow full optical characterisation of such pixels and allow an optical efficiency to be calculated effectively.

As the signals being measured at these short wavelengths are at an extremely low level, the throughput of the system must be maximised and so multi-mode systems are proposed. To this end, the focal planes of future far IR missions may consist of an array of multi-mode rectangular feed horns feeding an array of, for example, TES devices contained in individual integrating cavities. Such TES arrays have been fabricated by SRON Groningen and are currently undergoing comprehensive optical, electrical and thermal verification. In order to fully understand and validate the optical performance of the receiver system, it is necessary to develop comprehensive and robust optical models in parallel.

We outline the application of this developed rectangular mode-matching technique to the experimental testbed used at SRON Groningen in the optical testing of the TES arrays with multi-mode pyramidal horns. This testbed makes use of a blackbody source to illuminate the pixels both together and individually, and returns the power output from each of the TES detectors. The extension to the mode-matching technique to allow for the excitation of a pixel using the blackbody source is outlined, in addition to the method used in order to predict the power measured by the TES detectors from the mode-matching technique and the optical efficiency of the pixel. The simulated results are compared to the SRON measurements.

SAFARI (SPICA FAR infrared Instrument) is a far infrared imaging grating spectrometer, to be proposed as an ESA M5 mission. It is planned for this mission to be launched on board the proposed SPICA (SPace Infrared telescope for Cosmology and Astrophysics) mission, in collaboration with JAXA. SAFARI is planned to operate in the 1.5-10 THz band, focussing on the formation and evolution of galaxies, stars and planetary systems. The test pixel discussed in this paper is typical of one option that could be implemented in the SAFARI focal plane, and so the ability to accurately understand and characterise such pixels is critical in the design phase of the next generation of far IR telescopes.

9914-40, Session 8

Development of the multi-mode horn-lens configuration for the LSPE-SWIPE B-mode experiment

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The information contained within the B-mode component of the cosmic microwave background polarisation has the potential to constrain theories of cosmic inflation in the early universe. The extremely weak nature of the B-mode signal necessitates a measuring instrument with a high sensitivity and well controlled systematics. Furthermore, observations must be made over a wide frequency range in order to discriminate against the strong galactic foregrounds which contaminate the B-mode signal.

The Large Scale Polarisation Explorer (LSPE) is a balloon-borne experiment aiming to measure the B-mode at large angular scales. The Short Wavelength Instrument for the Polarisation Explorer (SWIPE) is a bolometric polarimeter observing in three bands centred at 140, 220 and 240 GHz. The telescope is a single large 480 mm diameter plano-convex

high density polyethylene lens. Polarisation sensitivity is achieved by means of a large metal-mesh rotating half-wave plate and a fixed wire grid polariser; feeding orthogonal polarisations onto two focal planes of back-to-back feed horns. Instrument sensitivity is boosted by allowing the feed horns to couple many higher order waveguide modes onto the bolometer. The main drawback of the multi-mode design is an increased complexity in the measurement and simulation of the optics and detector assembly. Thinking of the detector as a transmitter, the propagating electric fields produced by each modal excitation at the throat of the horn act incoherently and therefore must be simulated separately through the system, leading to long simulation times. Furthermore, each of these modal excitations is associated with a different coupling efficiency to the bolometer, which must be taken into account. Combining this with the large electrical size of the lens in SWIPE makes it a very challenging system to simulate.

Simulations have been performed to predict the multi-mode optical response (intensity and polarisation) of the horn-lens system for centre and off-axis pixels pertaining to each frequency band. The horn is simulated to a high accuracy using the full-wave simulation technique, the Method of Moments (MoM). Using the horn as a source, the optical response of the lens is examined using the more approximate simulation technique, Ray-Launching Geometrical Optics (RL-GO). Solution accuracy and simulation time depend heavily on the choice of RL-GO simulation parameters including: mesh size, maximum number of ray interactions and the angle between adjacently launched rays. Individual convergence studies are performed for each of these parameters and a final model is obtained as a compromise between simulation time and accuracy.

Another key factor in the design of the horn-lens system is the position of the telescope focus relative to the horn. For a single mode horn, the telescope focus is placed at the horn phase centre in order to optimise gain and angular resolution. The situation is more complicated for a multi-mode system since each modal excitation can produce a different location of phase centre. The optimal location of 'phase centre' has been investigated and compared using several techniques including: backwards propagation of the horn aperture field; and the translation of the lens in the full simulation.

9914-41, Session 8

Systematics of ambient temperature rapidly rotating half-wave plates

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We present an evaluation of the systematic errors associated with a rapidly-rotating, ambient-temperature half-wave plate (HWP) based on two seasons of data from the Atacama B-Mode Search (ABS) experiment located in the Atacama Desert of Chile. The HWP allows for rejection of unpolarized atmospheric fluctuations and ground pickup, as well as clear separation of celestial polarization from intensity. We present our in-field evaluation of celestial (CMB plus galactic foreground) temperature-to-polarization leakage and estimate its contribution to the systematic error budget of the ABS experiment. We decompose the leakage into scalar, dipole, and quadrupole terms. We report a scalar leakage of ~ 0.01%, which is consistent with model expectations and an order of magnitude smaller than any other CMB experiment. No significant dipole or quadruple terms are detected; we constrain each to be < 0.06% (95% confidence level). The upper limit on possible systematic error from these effects corresponds to a tensor-to-scalar ratio r ~ 0.01 with no mitigation due to scan strategy, including boresight rotation. This demonstrates that ABS is not systematic-error limited from the HWP at this level and shows the promise of fast polarization modulation with ambient-temperature HWPs for precision microwave polarization measurements.

9914-42, Session 8

The design and characterization of wideband spline-profiled feedhorns for Advanced ACTPol

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Advanced ACTPol (AdvACT) is an upgraded camera for the Atacama Cosmology Telescope that will measure the Cosmic Microwave Background in both temperature and polarization over a wide range of angular scales and five frequency bands from 28-230 GHz with unprecedented resolution and sensitivity. AdvACT's sensitivity, resolution, wide frequency coverage, and large sky coverage will enable it to simultaneously probe inflation at large angular scales while using small angular scale measurements to constrain the mass and number of neutrinos, dark energy, and dark matter. AdvACT will employ three arrays of feedhorn-coupled, polarization-sensitive multichroic detectors that are designed to maximize the focal plane area through minimizing the spacing between pixels on the array. To achieve this higher packing density, we have developed and optimized wideband spline-profiled feedhorns for the AdvACT multichroic arrays that maximize coupling efficiency while carefully controlling polarization systematics. The feedhorns are optimized via Markov chain Monte Carlo (MCMC) simulations to minimize the difference between the calculated E-plane and H-plane beams of the feedhorn over twenty frequencies within the multichroic observation bands while estimating the beam coupling efficiency. By using parallel MCMC optimizations, we have decreased the design time to a few days. To validate the feedhorn design before fabrication, we simulate the beams of each feedhorn in HFSS (an electromagnetic finite element method solver) then calculate the beam coupling efficiency, cross-polarization, return loss, far field beams including the instrument Lyot stop, and the polarization leakages in the power spectra assuming a pair differenced detector pair. This represents an extreme test of the performance since in AdvACT the half-wave plates will eliminate the need for pair differencing orthogonal pairs of detectors to gain polarization sensitivity and will provide significant extra mitigation of systematics. Once the monolithic Si feedhorn arrays are fabricated by the National Institute of Standards and Technology, we measure the feedhorn beams and return loss with an ambient-temperature vector network analyzer. We will present the design, fabrication, and testing of wideband spline-profiled feedhorns for the multichroic arrays on AdvACT.

9914-43, Session 8

Antireflection and gradient index layers for silicon optical elements utilizing deep reactive ion etch processing

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A broad range of applications in millimeter and submillimeter astronomy have benefited from the use of silicon optical elements, and silicon is likely to continue to be important in future applications both from the

ground and in space. The high refractive index and low loss of silicon at these wavelengths make it an ideal material for focusing optics, while the mechanical properties are suitable for constructing large diameter but low-loss vacuum windows. Antireflection treatment of silicon optics is essential, however, and has proven a major challenge for the 150 to 1000 millimeter diameter optics required for current and future applications. Moreover, multilayer antireflection treatments are necessary for wide spectral bandwidths, with wider bandwidths requiring more layers. It is difficult to find low-loss dielectrics with the correct refractive index and thermophysical properties to work well with silicon. Considerable success has been achieved at longer wavelengths by cutting matched layers into silicon surfaces with dicing saws, however, obtaining progressively larger bandwidths requires cutting of progressively more and deeper layers with thinner grooves, and the utility of this approach at higher frequencies is limited by the minimum feature size that a dicing saw can produce. While smaller features can be produced by deep reactive ion etch processing, this method is limited in the depth and aspect ratio of the produced features, and is unsuitable for use on thick and/or curved substrates.

We are investigating an alternative approach in which a silicon optic is produced by stacking multiple patterned wafers. The resulting optic is designed with an axial gradient in the refractive index for antireflection purposes, combined with a radial index gradient for focusing. Individual wafers are patterned with holes or pillars to achieve the required refractive index gradient, and multiple wafers are bonded together to produce the finished optic.

In this paper, we discuss the current status of the development program. The design, fabrication and performance of individual optical layers are presented, and the progress towards the production of the overall stacked optic is described.

9914-44, Session 9

Large arrays of dual-polarized multichroic TES detectors for CMB measurements with the SPT-3G receiver

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The cosmic microwave background (CMB) is remnant radiation from the early universe that provides a unique window for exploring fundamental physics. CMB detectors have evolved to the point where their sensitivity is limited by photon noise. Increasing the sensitivity of CMB experiments requires fabricating focal planes with orders of magnitude more detectors than current instruments. Large arrays of multichroic pixels constitute an economic approach to increasing the number of CMB detectors within a given focal plane area. Here, we present the fabrication of large arrays of dual-polarized multichroic transition-edge sensor (TES) bolometers for CMB measurements. These detectors will be used for the South Pole Telescope third generation CMB receiver (SPT-3G). Deployment of the SPT-3G receiver to the South Pole is planned for the end of 2016. The complete SPT-3G receiver will have ~2690 pixels. Each pixel has six detectors, allowing for individual measurement of three spectral bands (centered at 95 GHz, 150 GHz and 220 GHz), each in two orthogonal polarizations. In total, the SPT-3G focal plane will have 16140 detectors. Each pixel is comprised of a broad-band sinuous antenna coupled to a niobium microstrip transmission line. In-line filters are used to define the different band-passes before the millimeter-wavelength signal is fed to the respective Ti/Au TES sensors. The overall microfabrication involves a total of 16 processes, including reactive and magnetron sputtering, reactive ion etching, inductively coupled plasma etching and chemical etching. Patterns are defined using a combination of stepper and contact lithography. Together with the fabrication process, results on the pre-deployment cryogenic characterization of the fabricated detectors are presented.

9914-45, Session 9

Characterization of the first high density sub-mm multichroic array for the Atacama Cosmology Telescope

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The Advanced Atacama Cosmology Telescope Polarimeter (Advanced ACTPol) is a polarization sensitive receiver upgrade to the 6 m Atacama Cosmology Telescope. Advanced ACTPol adds new frequency bands on denser arrays to make measurements of the small angular scale polarization anisotropies in the Cosmic Microwave Background (CMB), and simultaneously constraining foregrounds. The improved sensitivity of the upgrade will permit new cosmological constraints on topics including the sum of the neutrino masses, dark energy parameters, and alternate models of gravity. The new receiver will comprise multichroic arrays, each covering two frequency bands spanning 30 GHz and 220 GHz. The receiver will be operated at 100 mK continuously using a dilution refrigerator. The first detector array is composed of 2024 feedhorn-coupled AlMn TES bolometers, fabrcated on a single 150 mm wafer; and read out through a 2-stage SQUID-based time division multiplexing scheme. We will present the optimization and characterization of the first detector array for the receiver, sensitive to both 220 GHz and 150 GHz frequency bands simultaneously.

A highlight of this work is that the detectors are fabricated for the first time on a 150-mm wafer. The wafer is then assembled with readout components, which all fit in a 12-inch diameter area. The resulting assembly is compact and dense. The use of 100 mK cryogenics improves the sensitivity significantly. High-density sensitive multichroic arrays are a critical component of proposed future CMB experiments, including the ground-based CMB Stage IV effort.

We will focus on first the design of the detectors which is driven by optimization of the detector performance. Next, we describe the characterization of the detectors using the novel ultra dense readout scheme, and conclude with projections of the detector on-site performance. We will cover the detector parameters tested in the laboratory and prediction of the achieved performance under different loading conditions on the telescope at the high-altitude site. The parameters presented will include the overall detector yield, the critical temperatures, thermal conductivities, saturation power, time constants and efficiencies and their uniformity across the 150-mm wafer.

9914-46, Session 9

Fabrication of 150/230 GHz multichroic polarimeter arrays for Advanced ACTPol

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Advanced ACTPol (AdvACT) is a third-generation cosmic microwave background (CMB) polarization-sensitive receiver that will be deployed as a multi-stage upgrade to the Atacama Cosmology Telescope (ACT) in Chile. Spanning five frequency bands from 25 GHz to 280 GHz and having just over 5600 transition-edge sensor (TES) bolometers, this receiver will provide increased sensitivity, increased mapping speed, and improved CMB foreground rejection compared to previously fielded ACT instruments. AdvACT, like the currently fielded ACTPol instrument, will employ the proven combination of silicon platelet feedhorns coupled to polarization-sensitive TES detectors. This technology provides repeatable band edges, excellent noise performance, fast time constants, excellent beam properties, and high coupling efficiencies. The AdvACT detectors build upon the ACTPol 90/150 GHz polarimeter architecture, with the same key components in each pixel – the feedhorns couple radiation via the orthomode transducer to orthogonally polarized Nb transmission lines, which connect to in-line stub filters that define two passbands prior to the signals being routed to a hybrid tee, which passes the lowest order mode to a thermally isolated AlMn TES. Each pixel consists of four TESs, allowing for individual measurements of two frequency bands, each in x- and y-polarizations.

With a goal of densely packed detectors on a monolithic substrate, we have migrated our traditional 3 inch diameter wafer array fabrication process to 150 mm diameter wafers. The 150/230 GHz AdvACT array, scheduled for deployment in early 2016, consists of 2012 individual AlMn-based TES bolometers. Many fabrication process improvements were specifically developed to increase array yield and uniformity and were required to meet the design specifications and desired performance improvements. The process has been streamlined by decreasing the total wafer count for a single focal plane from five 3 inch wafers to one 150 mm wafer and decreasing the total number of fabrication steps by 25%. By utilizing repeating rhombus-shaped pixels and wiring tracks, every front-side layer is patterned with non-contact stepped lithography in a close-packed arrangement. A partially automated layout code allows straightforward modification of pixel size, wiring width and pitch, and bond pad placement. An AlMn-alloy TES material has been developed with a uniform Tc (160 mK) across 150 mm, coarsely set by Mn concentration and fine-tuned by a post-deposition anneal. The dielectric loss has been reduced by switching to an optimized SiNx film from SiOx, resulting in a projected 10% increase in overall detection efficiency. A microwave cross-under structure has been designed and implemented that minimizes reflections and crosstalk between adjacent channels and also simplifies the fabrication process by eliminating the need for a third wiring layer. All of these improvements have been tested by fabricating and measuring prototype 150/230 GHz single pixels, which exhibit well-formed single-moded beams, good optical efficiency, and multichroic passband distinction that is well-matched to simulation. In addition to describing the process improvements and details of the 150/230 GHz HF array fabrication, we will present an update on the ACT instrument status that reflects the installation of the HF array.

9914-47, Session 9

Multimode bolometer development for the PIXIE instrument

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The Primordial Inflation Explorer (PIXIE) is an Explorer-class mission concept designed to measure the polarization and absolute intensity of the cosmic microwave background [1]. In this work, we report on the design, fabrication, and performance of the multimode polarization-sensitive bolometers for PIXIE, which are based on silicon thermistors. In particular we focus on several recent advances in the detector design, including the implementation of a tensioning scheme to greatly raise the frequencies of the internal vibrational modes of the large-area, low-mass optical absorber structure consisting of a grid of micromachined, ion-implanted silicon wires. With ~30 times the absorbing area of the spider-web bolometers used by Planck, the tensioning scheme enables the PIXIE bolometers to be robust in the vibrational and acoustic environment at launch of the space mission. More generally, it could be used to reduce microphonic sensitivity in other types of low temperature detectors. We also report on the performance of the PIXIE bolometers in a dark cryogenic environment.

[1] A. Kogut, et al., "The Primordial Inflation Explorer (PIXIE): a nulling polarimeter for cosmic microwave background observations," Journal of Cosmology and Astroparticle Physics, vol. 2011, issue 7, paper number 25.

9914-48, Session 9

Beam pattern optimization for the primordial inflation explorer (PIXIE)

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Measuring the B-mode polarization of the CMB radiation requires a detailed understanding of the projection of the detector onto the sky. The Primordial Inflation Explorer (PIXIE) uses a polarizing Fourier transform spectrometer to difference two co-pointed beams on the sky. We show a detailed analysis of the full PIXIE instrument including the telescope, FTS, and non-imaging concentrator. Small deviations from conic sections can significantly improve the beam shape in polarization. We discuss the importance of the m=2 mode for polarization and show how it can be improved for the full instrument response.

Both the details of the overall beam shape and the details of the polarization efficiency are important, however the operation of PIXIE allows separation and correction for all non m=2 modes. So the beam optimization concentrates on reducing the m=2 mode, while retaining the overall through-put of the instrument.

9914-99, Session PThu1

Design and measurement of a direct-drillable smooth walled feedhorn at 1.2 THz for the next generation BLASTPol experiment

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We present the design and measurement of a direct-drillable smooth walled feedhorn for the Next Generation BLASTPol balloon experiment. The 1.2 THz (250 micron) band Next Generation BLASTPol has over 600 dual polarization kinetic inductance detectors, each requiring a high performance, broad band dual polarization feed. The design presented here, based on a scaled version of a horn developed by Tan et al. (2012), is directly drillable with a custom single flute milling cutter. The horn is a modified Pickett-Potter type horn with three conical steps mated to a circular waveguide. Simulations show a high quality Gaussian beam with a bandwidth of approximately 30%. Custom milling cutters were obtained commercially and used to fabricate a two feedhorn structures with UG-387 flanges, each with a ? wavelength section of circular waveguide. These horns were then mated at the flange to produce a back to back feedhorn coupled by 1 wavelength of circular waveguide. These horns were then tested at Cardiff University using a rotation stage scanner to measure E and H plane cuts of the horn with a Fourier transform spectrometer operating in the band 840 GHz-1050 GHz. The measurements show good agreement in both the beam FWHM and sidelobes as compared to HFSS simulations of the horn. Scaled versions of the same horn will also be used for the 500 micron and 350 micron bands of the Next Generation BLASTPol instrument.

Tan, B-K, Leech, J., Yassin, G., Kittara, P., Tacon, M., Wangsuya, S., Groppi, C., A High Performance 700 GHz Feed Horn, Journal of IR, MM and THz Waves, v. 33, no. 1, pp. 1-5, 2012.

9914-103, Session PThu1

Simulations of far sidelobes produced by panel gaps in the Atacama Cosmology Telescope (ACT) and their effect in CMB power spectrum measurements

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The Atacama Cosmology Telescope is a 6 m diameter CMB telescope located at 5200 meters in the Chilean desert, producing maps of the sky's intensity and polarization at 150 and 90 GHz with arcminute resolution. These observations have led to precise measurements of the fine angular power spectrum of the CMB fluctuations in temperature and polarization. One of ACT's goals is to search for the B- mode polarization signal from primordial gravity waves, and thus to extend ACT's data analysis to larger angular scales. This goal presents new challenges in the control of systematic effects, including better understanding of far sidelobe effects that might contaminate the power spectrum at degree angular scales. Here we study the effects of the $\approx$ 2 mm gaps between panels comprising the ACT primary and secondary mirrors in the worst case scenario in which the gaps remain open. We produced numerical simulations of the optics using GRASP that extended up to 15 degrees away from the main beam, revealing the asymmetrical and polarized nature of the far sidelobes, which are also highly attenuated below the main beam. To understand their effects, a simulated CMB map was de-projected onto ACT-like detector time-streams using the simulated beam, together with the true angle and position information obtained from real observations. The time-streams where then re-mapped, averaging down the asymmetries of the beam in a realistic manner. The resulting maps where then analyzed, quantifying the systematic effects produced by the far sidelobes on the temperature and polarization angular power spectra.

9914-108, Session PThu1

Modeling multimode feed-horn coupled bolometers for millimeter-wave and terahertz astronomical instrumentation

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Multi-mode horn antennas can be utilized as high efficiency feeds for bolometric detectors, providing increased throughput and sensitivity over single mode feeds, while also ensuring good control of beam pattern characteristics. Multimode horns were employed in the highest frequency channels of the European Space Agency Planck Telescope, and have been proposed for future terahertz instrumentation, such as SAFARI for SPICA.

What differentiates a multimode horn from a single mode horn is the larger size of the waveguide feeding it, which allows higher order modes to propagate carrying extra power to the detector. If diffraction limited resolution is not required, as when observing extended faint sources, then the full increase in sensitivity of multimode horns can be utilized, otherwise a cold stop can be used to provide the required resolution.

Clearly, the efficiency with which the individual modes couple to the bolometer in the cavity will influence the overall beam pattern shape, as well as the aperture efficiency of the horn. It is usually assumed that a cavity mounted bolometer is a perfect black body absorber (as was done for the HFI 857 GHz and 545 GHz channels on Planck). However, this is an approximation and in this paper we present how this approach can be extended to actually include the cavity coupled bolometer, now modelled as a thin absorbing film. Generally, this is a big challenge in that the structures are typically electrically large. In this case the radiation pattern of multi-mode horns can be most efficiently simulated using mode matching, typically with smooth walled waveguide modes as the basis and computing an overall scattering matrix for the horn-waveguide-cavity system.

As well as predicting the horn beam pattern more precisely, we are also of course interested in investigating the cavity configuration for optimizing power absorption. Therefore, in the paper, as an example, the effects of offsetting the axis of a cylindrically symmetric absorbing cavity from that of a circular waveguide feeding it are discussed. This allows for the extra possibilities of power scattering between modes of different azimuthal orders, as well as also between the degenerate orthogonal pairs of modes (with the same radial field distributions) of a given azimuthal order. Another issue is the effect on the optical efficiency of the detectors of the presence of any gaps, through which power can escape. To model these effects requires that existing in-house mode matching software 'CylindricalSCATTER', which currently calculates the scattering matrices for axially symmetric waveguide structures, be further developed to be able to handle offset junctions and free space gaps ('OffsetSCATTER'). Results of the application of the 'OffsetSCATTER' software for various detector cavity offsets, feed waveguide lengths, detector sizes, surface resistances and detector positions within the cavity are also presented, along with the resulting multimode beam patterns. We will show how the approach can be applied to proposed terahertz systems, such as SPICA-SAFARI, and how multi-mode horns are also possible as feeds for CMB arrays for B-polarization experiments.

9914-112, Session PThu1

Optical design and modeling of the QUBIC instrument: a next-generation quasi-optical bolometric interferometer for cosmology

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The expansion of the universe has redshifted and therefore cooled the remnant radiation from the earliest epoch in the universe so that today it has a blackbody spectrum at a temperature of 2.73 K. It is known as the Cosmic Microwave Background (CMB). Hot Big Bang cosmologies predict that the CMB contains faint temperature and polarisation anisotropies imprinted in the early universe. Temperature measurements are effectively complete with the PLANCK satellite measuring exquisite detail out to multipole l=2500 (Ade, et al., 2013). The next logical step, albeit ambitious, is to map the primordial polarisation signatures which are expected to be several orders of magnitude lower than those of the temperature anisotropies. A suitable decomposition for this type of observation is into E-modes (curl-free) and B-modes (divergence-free). Using this decomposition, scalar sources (producing E-modes) and tensor sources (producing E- and B-modes) can be distinguished. Their relative amplitudes are described by, r, the tensor-to-scalar ratio. E-modes, a couple of orders of magnitude lower than the temperature anisotropies, were first detected by DASI (Leitch, et al., 2002) and by several follow-up missions. Primordial B-modes have to-date avoided detection as their magnitude is lower again. Their magnitude is unknown but PLANCK has placed an upper limit on, $r \leq 0.11$. Inflation theory predicts large scale (>1°) B-mode patterns in the CMB and their detection is a "smoking-gun" for Inflation. Detection of B-modes will require a sensitive telescope with exceptional control over systematics. The ground-based QUBIC (Q and U Bolometric Interferometer for Cosmology) instrument aims to provide this. It is based on the novel concept of bolometric interferometry in conjunction with synthetic imaging. Cryogenically cooled bolometers provide the sensitivity at the image plane. Fizeau interferometry with the aid of a novel auto-calibration technique exploiting the equivalent-baseline structure inherent in the aperture array will give the required control over systematics. Beams from an array of feed horns observing the sky will be combined quasi-optically. The optical-combiner is an off-axis compensated Gregorian operating in a dual band (150 and 220 GHz with 25% bandwidth) mode. Stokes parameters will be extracted directly from the synthetic image and the dual band nature will allow for foreground removal and detection of a tensor-to-scalar ratio, $r \geq 0.05$ with two years of data or $r \geq 0.04$ if PLANCK data are also used.

In this paper we outline the optical modelling of the QUBIC beam combiner. Beams from an array of 400 back-to-back ultra-Gaussian feed horns that observe the sky are combined. Modelling was carried out with a range of techniques, to account for the non-negligible diffraction effects and large component sizes at these frequencies. The techniques included ray-tracing, a Gaussian-beam-mode analysis and physical-optics. The modelling was implemented in the commercial package GRASP (TICRA, 2005) and MODAL (White, 2006; Gradziel, et al., 2008) which is software developed in-house by Maynooth University, Ireland. We describe the expected performance of the combiner and modelling work envisaged for the future.

9914-116, Session PThu1

Optical modeling and polarization calibration for CMB measurements with the ACTPol and advanced ACTPol

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The Atacama Cosmology Telescope Polarimeter (ACTPol) is a polarization

sensitive upgrade to the Atacama Cosmology Telescope, located at an elevation of 5190 m on Cerro Toco in Chile. ACTPol utilizes transition edge sensor bolometers coupled to orthomode transducers to measure both the temperature and polarization of the cosmic microwave background (CMB). Calibration of the detector angles is a critical step in producing polarization maps of the CMB. Polarization angle offsets in the detector calibration can cause leakage in polarization from E to B modes and induce a spurious signal in the EB and TB cross correlations.

We calibrate the ACTPol detector angles by raytracing the designed detector angle through the entire optical chain to determine the projection of each detector angle on the sky. These per detector calibrated polarization angles are consistent with a global offset angle of zero when compared to the EB-nulling offset angle, the angle required to null the EB cross correlation power spectrum. Here we present the optical modeling process which uses the commercial optical design software CODEV.

The calibrated design angles can be cross-checked through observations of known polarized sources, whether this be a galactic source or a man-made source. To cross-check the ACTPol detector angles we use a fine wire grid placed in front of the receiver of the telescope, after the primary and secondary mirrors. Making use of the Advanced ACTPol rapidly rotation half wave plate (HWP) hardware we spin the polarizing grid at a constant speed, polarizing and rotating the incoming atmospheric signal. The resulting sinusoidal signal is used along with angular position data from the HWP hardware to determine the detector angles.

The optical modeling calibration technique was shown to be consistent with a global offset angle of zero when compared to EB nulling in the first ACTPol results and will continue to be a part of our calibration implementation. The first array of detectors for Advanced ACTPol, the next generation upgrade to ACTPol, will be deployed in 2016. We plan to continue using both techniques and comparing them to astrophysical source measurements for the Advanced ACTPol polarization calibration.

9914-120, Session PThu1

Design and development of a room-temperature continuously rotating achromatic half wave plate for CMB polarization modulation on POLARBEAR-2

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The POLARBEAR-2 (PB2) experiment will study polarization fluctuations in the Cosmic Microwave Background (CMB) from the Atacama Desert in Chile starting in early 2017. In order to suppress 1/f noise due to unpolarized atmospheric turbulence and allow for study of degree-angular-scale CMB fluctuations, where the inflationary gravitational wave signal is thought to exist, polarization modulation is needed. The PB2 system projects a 365mm-diameter focal plane of 7588 dichroic, 95/150GHz transition edge sensor (TES) bolometers onto a 3-arcminute beam that scans at 1 degree per second. This system necessitates a large-aperture, low-thermal-emission, broadband modulator that can provide 100 seconds of detector stability. We present the development of a room-temperature continuously rotating achromatic half wave plate (HWP) as a polarization modulator for PB2. We first acknowledge promising experiences from third season PB1 HWP noise analysis. We then present the design requirements for the PB2 HWP, the results of our integration and evaluation of the HWP birefringent sapphire substrate, anti-reflection coating, and rotation mechanism, and the prospective impact of the HWP on PB2 noise performance, beam systematic mitigation, and galactic foreground subtraction. We conclude with a discussion of planned improvements for HWP instrumentation on future Simons Array receivers.

9914-123, Session PThu1

Optical design and verification of a 4mm receiver for the 20m telescope at Onsala Space Observatory

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The work of this research is the design, analysis and verification of the optical performance of a 4 mm receiver channel for the 20 m telescope at Onsala Space Observatory, Onsala, Sweden. This work was carried out at Maynooth University in collaboration with Onsala Observatory Onsala Space Observatory is the Swedish National Facility for Radio Astronomy. The 20 m and 25 m telescopes are used for studies of the formation of stars, and of molecules in the Milky Way and other galaxies.

The 4 mm (75 GHz) receiver is a newly proposed channel designed to be installed parallel to the existing 3 mm (100 GHz) channel targeting new science at that longer wavelength. The 4 mm receiver is designed to operate over the bandwidth between 67 GHz and 86 GHz. In order to have constant aperture efficiency over the band of interest, the optical layout is designed to be wavelength independent over this band. This is achieved by developing a two mirror system to image the horn antenna aperture to the secondary mirror of the telescope ensuring a constant beam size is achieved. As the receiver is contained within a cryostat unit, there are severe mechanical restrictions, which also have to be accounted for in the proposed optical design.

In the initial design, Gaussian beam mode analysis is used to produce the fundamental optical design of the system, as it is a computationally efficient method which provides all critical beam characterization through the optical train. Ray transfer matrix analysis is used to model beam transformation due to optical components. This method, also commonly known as ABCD matrix analysis, is adapted from geometrical analysis and makes use of the paraxial approximation. It is used to determine important parameters associated with the beam at certain planes in the system such as first order beam truncation and beam clipping.

The design is then analysed more accurately with the physical optics approximation. This allows a full aberration analysis to be included for the off-axis ellipsoidal mirror designs, as well as a full optical efficiency calculation when the propagated beam at the secondary mirror is coupled with an ideal beam from the sky. This technique allows full characterization of the system and the best design mechanically fitting into the cryostat was realized. Experimental verification of the realized optical design was carried out at Onsala Space Observatory allowing full verification of the simulations to be carried out. Near field measurements were used in the verification which can be compared with simulations directly due to the accurate mechanical testing and placement of scanning antennae. We report on the comparison of simulation and measurement and verification of the system design.

9914-126, Session PThu1

Submillimeter and far-infrared dielectric properties of thin films

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High-performance circuits and optical coatings play an important role in submillimeter and far-infrared astronomical instrumentation. In practice, vapor-deposited thin film dielectrics find widespread use because of their nearly ideal insulation, electromagnetic propagation and compatibility in fabrication. The complex dielectric function enables the study of the refractive and absorption properties of these materials as a function of frequency and not only provides important insights into the consistency of the derived optical properties but can be used to inform the suitability of candidate materials for service in their intended application.

An analysis approach will be presented and used to derive the complex dielectric function from observed transmittance spectra to within an accuracy of 4%. The underlying model will be shown to satisfy the requirements, causality and passivity, as set by the Kramers-Kronig relations. Dielectric functions found in the literature based on different profile line shapes, such as the Lorentzian, the Gaussian, the Voigt and the Classical Damped Harmonic Oscillator, will be briefly surveyed. While only the latter meets all of the above-mentioned criteria, the first three do not; however, their use is widespread due to their relative simplicity of implementation and generally acceptable accuracy in the infrared, but can lead to spurious long-wavelength spectral artifacts. A model based on the classical harmonic oscillator with a frequency-dependent damping will also be considered. This simple model meets all the requirements and suitably describes amorphous dielectric materials. The application of this dielectric function to the measured transmission spectra between 1 ?m and 300 ?m for low-stress silicon nitride and silicon oxide films will be presented.

9914-129, Session PThu1

An ultra-broadband optical system for ALMA band 2+3

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The Atacama Large Millimeter Array (ALMA) is the largest millimeter and submillimeter radio telescope in the world. It combines an array of 66 classical Cassegrain antennas providing high sensitivity between 35 and 950 GHz. This frequency range is divided in 10 bands with fractional bandwidths between 19 and 36%. Having a lifespan of at least 50 years, ALMA is carrying out a permanent upgrading program for every one of its subsystems. Regarding its receivers the program focuses on achieving better sensitivity and larger bandwidths at the RF and IF level.

Due to the lack of good amplifiers above 80 GHz astronomical receivers, including those of ALMA, use superconductor-insulator-superconductor (SIS) mixers as the first element in the receiving chain. However, nowadays, low-noise amplifiers based on high-electron-mobility transistors (HEMTs), combined with Schottky diodes, have the potential to achieve similar noise levels of traditional SIS mixers at the W Band. Moreover, HEMT amplifiers are inherently easier to use, have a wider bandwidth and are more stable than SIS mixers, promising, thus, a new generation of broadband receivers. For these reasons an international consortium has been formed to demonstrate this technology in a prototype receiver covering current Bands 2 and 3 of ALMA (67 to 116 GHz) corresponding to a fractional bandwidth of 54%. Such receiver may allow to perform new astronomical measurements not achievable by receivers covering the two bands independently. Moreover, it could vacate space inside the cryostat for new instrumentation.

Here we present the design, implementation and characterization of an optical system covering the full range of ALMA Band 2+3. Since the optics is the first subsystem of any receiver, low noise figure and maximum aperture efficiency are fundamental for best sensitivity. However, a conjunction of several factors as the large bandwidth, truncation set by existing cryostat apertures, dielectrical couplings, losses in the materials, construction constraints and cost limitations, makes extremely challenging achieving these goals. To overcome these problems, several options have been studied including reflective and refractive optics. So far, the most promising, complying with all constraints, is the latter. It consists of a corrugated horn, a modified Fresnel lens and an ortho-mode transducer (OMT).

Two corrugated horns, implemented using different methods of construction, were studied. One is a horn whose profile was optimized for best performance and ease of fabrication using a single-piece manufacturing process in a lathe. The other is a more classical corrugated horn implemented using a series of concentric rings. To minimize the noise contribution of the optical system a one-step zoned lens was selected. The parameters of the lens were carefully optimized to maximize the frequency coverage and reduce losses. Simulations indicate that the systems implemented with these elements have aperture efficiencies better than 81% and the lens, the mayor contributor to the noise, adds less than 5K to the receiver noise temperature. As OMT we have studied two designs based on a turnstile junction.

Two versions of the system were constructed and characterized. The results indicate an excellent performance in good agreement with simulations.

9914-133, Session PThu1

FreeCAD visualization of realistic 3D physical optics beams within a CAD system model

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The facility to realise the shape and extent of optical beams within a telescope or beamcombiner can aid greatly in the design and layout of optical elements within the system. Beyond the realm where raytracing is applicable however, it becomes much more difficult to realise accurate 3D beam representations which incorporate diffraction effects. It then is another issue to incorporate this into a CAD model of the system.

A novel method is proposed which has been used to aid with the design of an optical beam combiner for the QUBIC experiment operating at 150GHz and 220GHz. The method combines calculation work in GRASP, a commercial physical optics modelling tool from TICRA, geometrical work in Mathematica, and post processing in MATLAB. Finally, the python console of the open source package FreeCAD is exploited to realise the 3D beams in a complete CAD system-model of the QUBIC optical beam combiner.

GRASP is used to measure the beam at sample grids which are perpendicular to the axis of propagation, these grids are spaced regularly along the beam path with positions chosen by trading off between calculation time and the detail necessary.

The individual grids are then analysed in MATLAB and the extent of the beam to be realised can be chosen. The footprint of the beam on each grid can be determined as that enclosed by a contour of a particular level where each grid is normalised to the peak power level on the grid. Alternatively the footprint on each grid can be determined as a circle which encloses a certain specific fraction of the initial beam power. The

percentage power method has the disadvantage that it returns circular beams however the contour method breaks down in quite distorted beams as 3D Beams cannot be constructed by this method from grids that return more than one independent contour of the chosen level.

The 2D locations of the chosen footprint on grids are then realised into a 3D beam by "stitching" the footprints appropriately from successive grids into a 3D mesh object through creating trigonal facets from the points. This mesh is then transformed to the reference frame used in the CAD system-model. Finally the python console in FreeCAD allows these 3D beams to be visualised within the CAD system-model.

In the analysis of the QUBIC beam combiner presented here, 3D beams of chosen footprints are shown in situ in the CAD system-model for various different horns of the 400 horn design, the -3dB and -13dB contour envelope is shown as well as envelopes enclosing 80% and 95% of the power of the beam. In an ideal Gaussian, the -3dB and -13dB contours enclose 50% and 95% of the Gaussian beam power. It is shown how the ability to see these beams in situ with all the other elements of the combiner such as mirrors, cold stop, beam splitter and cryostat widows etc. greatly simplified the design for these elements and facilitated communication of element dimension and location between different subgroups within the QUBIC group.

9914-137, Session PThu1

Silicon metamaterial optical elements for measurement of the cosmic micro-wave background

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Precision measurements of the polarization of the Cosmic Microwave Background (CMB) are a promising avenue for advancing our knowledge of the cosmos, putting constraints on the scalar to tensor ratio as well as the sum of the neutrino mass. In order to put meaningful constraints on these cosmological parameters, a wide range of frequencies are needed for foreground removal. Next generation instruments require broadband antireflection (AR) coated lenses to accommodate multichroic detectors and half-wave plates (HWPs) to suppress 1/f noise and telescope systematics. We describe progress on metamaerial AR coatings and a novel approach to broadband HWPs.

The AR coatings are realized by cutting subwavelength features into the silicon using a custom dicing saw. We have already created several such AR coated silicon lenses, which are currently deployed on the Atacama Cosmology Telescope (ACT) mid-frequency (90-150 GHz) band, and planned for their high frequency (150-220 GHz) and low-frequency (20-40 GHz) bands. The band average reflection for these three layer structures is less than 0.3%, and can be fabricated with high yield. Our designs can be extended to higher frequency in the THz range by cutting thinner features. We can also extend to very broadband coatings by increasing the number of layers. We have fabricated a prototype coating which is expected to reduce reflection below 1.5% over a 5:1 bandwidth.

Metmaterial HWPs are realized by cutting anisotropic features into single crystal silicon to create low loss birefringent metamaterial layers. Using this technique, we created a novel broadband polarization modulator by forming a three layer Pancharatnam structure realized by three cutting half-wave plates into two silicon wafer and gluing them together. A novel birefringent silicon AR coating optimized to minimize differential reflection was created on the two outer surfaces. We describe a design optimized for 2.2:1 bandwidth, covering both the 90 and 150 GHz CMB bands.

9914-101, Session PThu2

Optical characterization of the BICEP3 CMB polarimeter at the South Pole

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BICEP3 is a small-aperture refracting cosmic microwave background (CMB) telescope designed to make sensitive polarization maps in pursuit of a potential B-mode signal from inflationary gravitational waves. It is the latest in the BICEP/Keck Array series of CMB experiments located at the South Pole, which has provided the most stringent constraints on inflation to date. For the 2016 observing season, BICEP3 was outfitted with a full suite of 2500 detectors operating at 95 GHz. In these proceedings we report on the far-field beam performance using calibration data taken during the 2015-2016 summer deployment season in situ with a thermal chopped source. We characterize the differential beam response between co-located, orthogonally polarized detectors, which contributes to the leading systematic in pair differencing experiments. The magnitude and distribution of BICEP3's differential beam mismatch -- and the level to which temperature-to-polarization leakage may be marginalized over or subtracted in analysis -- will inform the design of next-generation CMB experiments with many thousands of detectors.

9914-105, Session PThu2

Data-driven electothermal and noise modeling of TES detectors in multichroic arrays for Advanced ACTPol

Kevin T. Crowley, Steve K. Choi, Princeton Univ. (United States); Advanced ACTPol Collaboration, Advanced ACTPol Collaboration (United States)

The future of the Atacama Cosmology Telescope (ACT) is the Advanced ACTPol (AdvACT) upgrade, featuring three types of dual-frequency, polarization-sensitive focal-plane arrays for a total of five observing frequency bands. The detectors at the heart of these arrays will be manganese-doped aluminum transition edge sensors (TESes). Currently, the first fielded dual-frequency array is observing as part of the ACTPol mission, with bilayer MoCu TES detectors in the focal plane. Understanding the detector response in situ, under instrumental loading conditions in the ACTPol cryostat, is crucial both to ACTPol and the AdvACT arrays which will use the same cryogenics.

Here we report on a campaign of dedicated data acquisition to create a detailed electrothermal picture of the MoCu superconducting bilayers. The data sets used include high sample-rate complex impedance and detector noise data. The last two complement each other and allow exploration of the fine details of detector response throughout the superconducting transition. Specifically, electrothermal model parameters estimated from complex impedance data at various TES resistances can be used to map detector parameters on the transition and to predict the expected noise spectra.

This method is equally applicable in the laboratory and the field, and thus the report includes early laboratory results on the electrothermal modeling of the AlMn TESes being fabricated for inclusion in AdvACT's high-frequency array. We plan a program of evaluating the noise characteristics of these AlMn TESes across the transition at bath temperatures chosen to mimic the anticipated field conditions. The measurements can be compared to the expected noise level calculated from the thermal properties of the detectors as measured with other datasets. Combined with a measurement of the detector optical efficiency using a cold blackbody load and the simulated model of the detector bandpass, these data can be extrapolated to predict the array sensitivity under observing conditions at the telescope.

Taken together, the field and laboratory high-frequency noise data in concert with more direct probes allow us to determine the detailed response of both types of detectors. In the case of AlMn TESes, this information may lead to ways to improve their design for future arrays. Finally, we intend to compare the electrothermal response of the doped superconductor (AlMn) and bilayer (MoCu) TESes.

9914-110, Session PThu2

The QUIJOTE TGI control system

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The QUIJOTE TGI (Therty GHz) instrument is currently being installed and commissioned at the Izaña Observatory in Tenerife. The TGI is a 30 pixel 26-36 GHz polarimeter array designed to be mounted at the focus of the second QUIJOTE telescope which has already been commissioned during the first months of 2015. This follows a first telescope and multi-frequency instrument (MFI) that have now been observing for more than 3 years. The polarimeter design is based on the QUIET polarimeter scheme implementing phase switches of 90º and 180º to generate 4 states of polarisation. The TGI control system acquires the scientific signal of the 4 channels for each of the 30 polarimeters, sampled at 160KHz; it controls the commutation of the 30 phase switches; it performs the acquisition and monitoring of the health of the complete instrument acquiring housekeeping from the different subsystems and also controls the different operational modes of the telescope. It finally, implements a queue system which allows to automatize the observations allowing the programming of several days of observations with a minimum human intervention. The telescope is a replica of the first telescope that hosts the MFI, but it has been improved by the inclusion of some safety boards as well as important mechanical issues. The operational modes are the movement around the azimuth axis at a constant velocity while the elevation axis is held at a fixed elevation; tracking of a sky object; and raster of a rectangular area both in horizontal and sky coordinates. The acquisition system is based on a PXI-RT host from NI which performs the acquisition, processing and transfer of the scientific data. A PXI-FPGA subsystem, also from NI, performs the commutations of the phase switches and a PC receives and stores data from the different subsystems, monitor the health of the instrument and implements the user interface. The 120 channels are sampled at 160KHz at the RT host and a real time processing is performed which allows to decrease the final transfer and storing rate to 4K Samples/sec. The FPGA subsystem generates the signal to commutate each of the 30 phase switches at 16KHz or 8KHz commutation producing 16 different states which are also averaged to obtain scientific measurements at 0º, 90º, 180º and 270º. Both the signal sampling and the commutation are synchronized with an external GPS system through NTP. The same clock is used to synchronize the telescope, providing the mechanism to reference the scientific signal with the sky to provide polarization maps. Two separate PCs provides the user interface, the first one receives and stores the scientific signal as well as the telescope positions; it also acquire and monitor the housekeeping of all subsystems. A second PC allows to

automatize observations by commanding both the acquisition system and the telescope. The control system software have been implemented mainly in LabVIEW with the support of some C dlls and Python has been used for the implementation of the observations queues.

9914-114, Session PThu2

Measurement concept of the PILOT instrument, pre-flight optical characterization, and optimization performed during end-to-end ground tests

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Future cosmology space missions will concentrate on measuring the polarization of the Cosmic Microwave Background (CMB), which potentially will bring invaluable information about the early universe. In particular, detection of the B-mode polarization may reveal the inflationary periods in the very early universe. Such measurements will require very high sensitivity and very low instrumental systematic effects. As for measurements of the CMB intensity, sensitive measurements of the CMB polarization will be made difficult by the presence of foreground emission from our own Milky Way. Such foreground emission will have to be understood very accurately and removed from cosmological measurements. This polarized emission is also interesting in itself, since it brings information relevant to the process of star formation and about the orientation of the magnetic field in our Galaxy through the alignment of dust grains. For measuring the foreground, we have developed the PILOT balloon borne experiment, which measures the linear polarization of diffuse interstellar medium in far-infrared in our Galaxy and nearby galaxies.

PILOT has a large field of view about 0.8°?1° and maps the galactic plane and deep fields during a 24 hrs flight at 40 km altitude. The instrument is composed of a 1 m diameter telescope and a Helium 4 dewar accommodating the rest of the optics and 2 focal plane arrays with a total of 2048 individual bolometers cooled down to 300 mK, developed for the PACS instruments on board Hershel satellite. It operated in one photometric band centered at 240 ?m (1.2 THz) in the first flight with an angular resolution of 2 arcminutes. Polarization is measured using a step and stare half-wave plate. The system is designed in order to reduce instrumental systematic effects. End-to-end calibration tests were performed between 2012 and 2014 in order to prepare the first scientific flight in September 2015 from Timmins, Canada.

Firstly, I will summarize briefly our current knowledge in this field, on the basis of extinction and emission measurements from the ground and airborne experiments and in the context of the recent measurements with the Planck satellite which PILOT will be able to complement for short wavelength. Then, I will describe the concept and science goals of the PILOT. After, I will focus on the ground calibration results to characterize the optical performance of PILOT including image quality control over the extended focal plane, defocus tests, focal plane geometry, and identification of internal straylight.

9914-117, Session PThu2

Dielectric sheet calibrator for measuring polarization angles of Keck Array Telescope

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The BICEP2 and Keck Array telescopes measure(d) CMB polarization with orthogonal Transition Edge Sensor-coupled antennas. An uncertainty in the polarization axis of the detectors leads to a mixing of E-to-B mode power. Because temperature fluctuations and E-mode polarization are correlated, this uncertainty also leads to a false correlation between temperature and B-modes. If the goal is only to measure B-mode power, one option is to rotate the polarization angles of the focal plane in order to minimize EB and TB correlation. However, this minimization prevents us from measuring or putting upper limits on any possible cosmic birefringence. We aim to measure the polarization angles of our detectors to better than 0.1 degrees.

With a rotating polarized source in the far-field and a Dielectric Sheet Calibrator (DSC) in the near-field, we measure the polarization angles of our detectors. In these proceedings we focus on the DSC, which is a thin beam-filling plastic film that acts as a beam splitter. Most of the beam is transmitted to the cold sky while a portion is reflected to a warm forebaffle. When rotating the DSC, the detectors see polarized signals, modulated at 360 degrees, that depend on the polarization axes of the detectors and the incident angles of the beams on the dielectric film. We present the design of the DSC for use with the Keck Array telescope. We also show how uncertainties in the measurement process propagate to uncertainties of the polarization angle calibration.

9914-121, Session PThu2

Assembly and integration process of the first high density detector array for Atacama Cosmology Telescope

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The Advanced Atacama Cosmology Telescope Polarimeter (Adv ACTPol) is an upgrade of the Atacama Cosmology Telescope (ACT) using Transition Edge Sensor (TES) detector arrays to measure CMB polarization anisotropies in multiple frequencies. The whole detector array consists of several major parts, including the feed horn and detector wafer stack, mux chips which serve as time division multiplexer and shunt chips for mux's bias tuning, series array board which contains SQUID module for signal amplification, printed circuit board (PCB) which connects chips to series array board through cables and wire bonding, and the flexible circuitry (flex) which connects detector wafer stack to PCB.

AdvACTPol will implement a new type of multiplexer chips (mux-13c) to achieve higher Multi-Channel Electronics (MCE) utilization efficiency and twice the number of total transition-edge sensors (TES) as compared to ACTPol. However, the consequent change of the readout PCB's design and the smaller size of the new mux chips, create significant challenges for finding practical detector array assembly processes. One major challenge concerns the success rate of wire bonding and the strength of wires, since the total number of wires is on the scale of 20,000 and each single wire is associated with 32 or 64 TESes. Mounting silicon wiring chips, on which mux chips and shunt chips are held by Stycast epoxy, to the PCB with rubber cement simultaneously solves the issue caused by differential thermal contraction of the chips and the PCB in a cryogenic environment and the wire-bonding problem. Additionally, jigs to secure the PCB while bonding, as well as new gluing methods of chips and the flex are also invented to improve the wire bonds' performance. Another challenge is the need for accurate alignment between the detector wafers, the PCB, and other affiliated parts including wiring chips and flexes. A displacement of several tenths millimeter would cause severe misalignment since the PCB and flex bond pad widths are on the scale of 100 micron. Vacuum wafer jig, wafer transfer jig, copper ring which holds the entire PCB, and flex gluing jig are all designed as a consequence of the higher requirement of alignment accuracy. These jigs vacuum-hold their corresponding parts in order to align all array components with each other through L-brackets and dowel pins. The aforementioned assembly process and methods would be advantageous for even denser detector assembly in the future.

9914-124, Session PThu2

Multi-band millimeter-wave polarimeters for advanced ACTPol

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We describe the designs and performance of prototype feedhorn-coupled, multi-chroic polarimeters of the third-generation camera for the Atacama Cosmology Telescope (ACT), referred to as Advanced ACTPol. Recently, the Planck and BICEP/KECK experiments have established that measurements of the Cosmic Microwave Background (CMB) polarization signal is limited, in part, by polarized foreground emission. In particular, polarized emission from galactic dust has been found to dominate and obscure potential signals of cosmic inflation, even in regions of the sky specifically identified as having relatively low galactic emission. Advanced ACTPol aims to address the foreground contamination by conducting observations of half the sky with broad spectral coverage spanning 25--280 GHz. Utilizing five discrete bands within this frequency range, the spectral coverage will allow differentiation within the measured signal between foreground sources of polarization and that of the CMB, which have different spectral characteristics. To cover such a large spectral range, the NIST-fabricated multi-chroic polarimeter arrays of Advanced ACTPol will comprise three different designs, each sensitive to a different pair of frequencies bands: a low-frequency (LF) polarimeter with bands centered at 28 and 41 GHz; a mid-frequency (MF) polarimeter at 90 and 150 GHz; and a high-frequency (HF) design operating at 150 and 230 GHz. Here we present the detailed mm-wave pixel design. Incoming radiation is coupled through a beam-forming feedhorn and waveguide to an orthomode transducer (OMT) that separates the radiation to two orthogonally polarized signal paths. A diplexer consisting of in-line microstrip filters further separates each polarization state into two frequency bands. A microstrip hybrid tee is used to reject undesired modes before the radiation is deposited on an AlMn transition edge sensor (TES) detector. In total, each pixel comprises four TES devices that together provide simultaneous sensitivity to two orthogonal polarization states in two frequency bands. We also present up-to-date characterization of the latest prototypes and/or final architecture (HF pixel development is complete). Measured performance qualities to be discussed include optical efficiency, polarization response, passband response, differential beam properties, and TES electrothermal properties. The three focal planes of Advanced ACTPol will each consist of monolithic NIST-fabricated polarimeter arrays fabricated on 150 mm silicon wafers and coupled to the ACT optics via silicon-platelet feedhorn arrays. Advanced ACTPol will be deployed as staged upgrades to the existing ACTPol camera, beginning with the new HF array to be installed in the second quarter of 2016.

9914-127, Session PThu2

Mechanical designs and development of TES bolometer detector arrays for the Advanced ACTPol experiment

Jonathan T. Ward, Univ of Pennsylvania on behalf of the Advanced ACTPol Collaboration (United States)

The Atacama Cosmology Telescope (ACT) is a six-meter diameter telescope located at 17,000 feet (5,200 meters) on Cerro Toco in the Andes Mountains of northern Chile. The next generation Advanced ACTPol (AdvACT) experiment is currently underway and will consist of four multichroic TES bolometer arrays operating together, totaling ~5800 detectors on the sky. Each array will be sensitive to two frequency bands: a high frequency (HF) array at 150 and 230 GHz, two middle frequency (MF) arrays at 90 and 150 GHz, and a low frequency (LF) array at 28 and 41 GHz. The AdACT detector arrays will feature a revamped design when compared to ACTPol, including a transition to 150mm wafers equipped with multichroic pixels, allowing for a more densely packed focal plane. Each set of detectors consists of a feedhorn array of stacked silicon wafers which form a corrugated profile leading to each pixel. This is then followed by a four-piece detector stack assembly of silicon wafers which includes a waveguide interface plate, detector wafer, backshort cavity plate, and backshort cap. Each array is housed in a custom designed structure manufactured out of gold-plated, high purity copper. In addition to the detector array assembly, the array package also encloses the majority of our readout electronics. We present the full mechanical design of the AdvACT HF and MF detector array packages along with a detailed look at the detector array assemblies. This experiment will also make use of extensive hardware and software previously developed for ACT, which will be modified to incorporate the new AdvACT instruments. Therefore, we discuss the integration of all AdvACT arrays with pre-existing ACTPol infrastructure.

9914-132, Session PThu2

Systematic error mitigation for the PIXIE instrument

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The Primordial Inflation Explorer (PIXIE) uses a nulling Fourier Transform Spectrometer to measure the absolute intensity and linear polarization of the cosmic microwave background and diffuse astrophysical foregrounds. PIXIE will search for the signature of primordial inflation and will characterize distortions from a blackbody spectrum, both to precision of a few parts per billion. Rigorous control of potential instrumental effects is required to take advantage of the raw sensitivity. PIXIE employs a highly symmetric design using multiple differential nulling to reduce the instrumental signature to negligible levels. We discuss the systematic error budget and mitigation strategies for the proposed PIXIE mission.

9914-135, Session PThu2

Calibration techniques for the primordial inflation explorer (PIXIE)

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The Primordial Inflation Explorer (PIXIE) compares the sky to an external blackbody calibrator to search for distortions in the blackbody spectrum of the cosmic microwave background at the 10 parts-per-billion level.

Achieving this goal requires accurate transfer of an absolute calibration standard from the time-ordered data to the final sky maps and spectra. The PIXIE calibration is based on a full-aperture blackbody calibrator.

The calibrator is similar to a compact blackbody flown on the ARCADE-2 balloon instrument but with improved optical and thermal performance. We discuss the PIXIE blackbody calibrator and the methods used to transfer the calibration from the raw time-ordered data to the final sky maps and spectra.

A significant improvement comes from allowing the either the calibrator or the sky on either input of the instrument. This allows a factor of 2 reduction of uncertainty in comparing the sky to the calibrator. It also eliminates systematic differences between the sky data and the calibration data as the measurements and the calibration use the same data.

9914-98, Session PThu3

The initial characterization of a revised 10-Gsps analog-to-digital converter board for radio telescopes

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In this study, the design of a 4 bit, 10-gigasamples-per-second analog-to-digital converter (ADC) printed circuit board assembly (PCBA) was revised, manufactured, and tested. It is used for digitizing radio telescopes. Two model of Adsantec flash ADC chips were used, ANST7120-KMA as in the original design and a just released ANST7120A-KMA. Associated with the field-programmable gate array platform developed by the Collaboration for Astronomy Signal Processing and Electronics Research (CASPER) community, the developed PCBA provides data acquisition systems with a wider bandwidth and simplifies the intermediate frequency(IF) section. The current version of the PCBA exhibits an analog bandwidth of up to 10 GHz (3 dB loss), and the chip of ANST7120-KMA exhibits an analog bandwidth of up to 18 GHz. The just released chip ANST7120A-KMA exhibits an analog bandwidth of up to 20 GHz . This facilitates second, third Nyquist and fourth Nyquist sampling. The following worst-case performance parameters were obtained from the revised PCBA with the chip of ANST7120-KMA at over 5 GHz: spurious-free dynamic range of 12 dB, signal-to-noise and distortion ratio of 2 dB, and effective number of bits of 0.7. The design bugs in the ADC chip of ANST7120-KMA caused the poor performance. The worst-case performance parameters from the revised PCBA with the chip of ANST7120A-KMA at over 5 GHz: spurious-free dynamic range of 27 dB, signal-to-noise and distortion ratio of 23 dB, and effective number of bits of 3.3. The chip of batch ANST7120A-KMA is the new version inherited from the ANST7120-KMA with bugs removed, thus it outperforms the original batch, and all the performance is reasonable to the standard of a four bits ADC.

By acquiring hardware from the CASPER community scientific institutes can save resources. Various ADC boards, with sampling rates ranging from a couple hundred MHz to 3 gigasamples per second (Gsps), are available through CASPER. The fastest sampling rate was 3 Gsps before the authors fabricated a 5 Gsps ADC board in 2012. After the success of the 5-Gsps ADC PCBA, a 10-Gsps ADC chip manufactured by Adsantec (ANST7120A-KMA) was selected as the key component in this study.

The architecture of the revised PCBA is highly similar to the original design, except for the input signal layout and a few minor modifications. The board comprises four key components: one 10-Gsps ADC chip, two demultiplexing chips (ANST2032-MBL), and one clock buffer. The ASNT5020-PQD high-speed analog clock buffer (Adsantec) was replaced with the NB6L11M buffer (ON Semiconductor). The performance of the new clock buffer met the study requirements at a lower cost.

With the wide bandwidth up to fourth Nyquist zone of the PCBA and the chips, the IF and Local Oscillation (LO) section can be further simplified.

That allows only the low pass and bandpass filters needed for the IF/LO system. The usual down-converting scheme in radio telescope to manipulate the radio frequency (RF) to the baseband frequency will not be necessary.

9914-104, Session PThu3

Detecting anomalies in astronomical signals using machine learning algorithms embedded in a FPGA

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Taking a large interferometer for radio astronomy, such as the ALMA telescope, where the amount of stations (64 in the case of the ALMA main array) produces a huge amount of data in a short amount of time (visibilities every 16msec or total power information every 1msec), it is becoming more difficult to detect problems in the signal produced by each antenna in a timely manner (one antenna producing 4 x 2GHz spectral windows x 2 polarizations, meaning a 16 GHz bandwidth signal, which is digitized using 3-bits samplers).

Under this context there is a wide range of possible issues which may cause corruption, or no sense data. Among these problems we can list:

- Big DC component introduced during the digitization step
- Reflections in the IF signal
- Unexpected spectral features (discontinuities or spikes)
- Harmonics
- Loss of coherence

The aforementioned signal inconveniences are not always detected promptly and the troubleshooting process can be a cumbersome task for scientists, especially during critical observation campaigns under a tight schedule or array constraints. Detecting those kinds of problems can take a considerable amount of time and the inability to detect them sooner can cause data losses during the subsequent observations.

This work presents an approach for detecting the previously listed types of problems in a real time manner. The already available logic resources (FPGA) will be the foundation for this new feature. Therefore no new hardware will be deployed for implementing this feature and, in addition, the software infrastructure will be marginally changed (the idea is to only add 16 monitor points and provide an alarm system to be used by the telescope operators).

Our proposal includes the use of machine learning algorithms for classifying and detecting signals which are presenting problems like the ones listed previously. The proposed algorithm will access a set of collected results from the correlator output and according to the method to be defined, a trained response will be able to recognize if the output at a certain instant is accepted, or whether it belongs to the list of acknowledged signal errors. As this work continues to grow, this tool will be able to detect more problems related to any antenna or correlator subsystem.

This work will present an approach which can be implemented using the information provided by the correlation function. Methodologies for extracting signal statistical features will be analyzed. Methodologies for validating the detection of signal problems will be analyzed. Performance of the classification engine will be tested.

The aim of this work is to produce a non invasive sub-system which can provide real time alerts if a signal were to show problems. In addition, one of the objectives is to reduce the usage of logical resources as much as possible.

The preventive alert system proposed in this work will allow astronomers to promptly flag a certain antenna and, according to the results given by this tool, follow up the problem immediately with instrumentation experts avoiding the offline analysis done as today and to dramatically speed up the troubleshooting process.

9914-109, Session PThu3

The FDM readout system for the TES bolometers of the SWIPE instrument of the balloon-borne LSPE experiment

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The LSPE balloon-borne experiment aims at measuring the linear polarization of the Cosmic Microwave Background at large angular scales to find the imprint of inflation on the B-mode CMB polarization by means of a 15-days circumpolar flight in the northern hemisphere during the 2017 polar night (see P. de Bernardis et al, contribution at this conference).

The Short Wavelength Instrument for the Polarization Explorer (SWIPE) onboard the LSPE balloon is composed of two facal planes hosting 170 TES Au/Mo spiderweb bolometers each, cooled at 0.3K for the detection of microwave frequencies of 140, 220 and 240 GHz to disentangle the contribution given by dust foregrounds.

To readout all the detectors a 16 channel frequency domain multiplexing readout system has been devised. It consists of a set of cold LC resonators composed of custom Nb superconducting inductances and SMD capacitors with a resonance frequency range between 200 kHz and 1.6 MHz, grouped in set of 16, each set being readout by a single SQUID amplifier. The tuned filter limits the bandwidth of the current noise of the TES and allows multiple detectors to be biased and read-out with a single pair of wires. The TES biasing, modulation and demodulation of the signals are managed by a readout system built around a MicroSemi SmartFusion2 system-on-chip model M2S150 that includes a powerful FPGA core with 150K LUT and an ARM processor with 167 MHz speed coupled to the necessary ADC and DACs to sinthesize the multiple sinusoids and read-out the signals modulated by the change in resistance of the TES bolometers induced by the physical signal.

The chosen DAC (LTC1668) was selected for its low noise and low power properties, while the ADC will be an AD9266 with a sampling speed of 20 MHz.

We will present the design of the system and tests of a partial set-up consisting of a sub-set of LC resonators driven by a prototype FDM board and read-out by a single SQUID showing that the packing factor and the necessary line-widths can be achieved, together with a preliminary firmware for the generation and read-out of the biasing frequency comb.

The superconducting inductances have been designed after suitable simulations at INFN Pisa and realized in NEST SNS Pisa facilities. They are assembled in the 4K readout chain in INFN Pisa clean-rooms. The circuits are tested in a cryogenic facility at INFN Pisa composed of a cryostat equipped with a 4K pulse tube refrigerator.

The roadmap towards the assembly and integration of the readout chain using the TES bolometers produced at INFN Genova (see M. Biasotti et al. contribution at this conference) will be discussed.

9914-113, Session PThu3

A real-time KLT implementation for radio-SETI applications

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The Search for ExtraTerrestrial Intelligence (SETI) is a project whose goal is to find possible life signatures emitted (intentionally or unintentionally) by possible civilizations from other habitable planets.

Historically, the narrow-band FFT approach has been used to detect intentionally-transmitted signals, since a quasi-monochromatic signal is expected to be among the probable ones to be used for sending a message to another distant world.

Nevertheless, we could receive an unintentionally-transmitted signal as well. In that case, it would most certainly not be a quasi-monochromatic signal, but would probably be similar, with a wider bandwidth, perhaps of the order of MHz, to the signals that we use for conventional communications on Earth.

The Kahrunen-Loeve Transform is a powerful algorithm for such a kind of research. To see why the KLT can, in some areas, be better than FFT, we consider an analogy with mechanics. Let us take as an example a book and a reference system composed of three Cartesian axes. In accordance with classic mechanics, all of the book's properties concerning the rotational dynamics can be described by a symmetric 3x3 matrix called the "inertia matrix". As is well known, computing the autocorrelation is a good method for extracting a signal immersed in noise.

Let us consider the autocorrelation to be the book itself; the eigenvectors of the autocorrelation matrix can then be calculated so as to find the best data representation. This is the idea behind the KLT.

However, a real-time implementation of the KLT has thus far not worked due to a lack of technological resources.

In this paper, we describe a hardware-software infrastructure at the new 64-m diameter Sardinia Radio Telescope (SRT) that makes it possible. Currently, the three receivers available at the telescope are: the dual-frequency L-P band (305-410 MHz, 1300-1800 MHz), the mono-feed high-C band (5.7-7.7 GHz) and, finally, the seven-feed K-band (18–26.5 GHz) receivers; other receivers (mono-feed low-C band (4.2-5.6 GHz), seven-feed S-band(3-4.5 GHz)) are under development.

Since SETI research is often conducted in piggyback mode only, a dedicated conditioning module was developed at the level of the intermediate frequencies. In particular, it acts as a frequency compensation mechanism that is necessary for keeping the chosen bandwidth stable even when a Doppler tracking system is activated, or in case the chosen bandwidth changes completely during the observation.

The data processing is distributed among FPGA-based boards developed by CASPER (Collaboration for Astronomy Signal Processing and Electronics Research) and named ROACH (Reconfigurable Open Architecture and Computing Hardware), and some GPU-based nodes. The first stage, implemented on the ROACH board, consists in splitting up the entire bandwidth into smaller pieces using the polyphase filter bank technique. In the second stage, a particular sub-band is sent to the GPU-based host in which the KLT runs.

We also show some results achieved during laboratory tests and on data acquired at the SRT.

9914-119, Session PThu3

Inflight characterization and correction of the Planck HFI analog to digital converter nonlinearity

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The Planck satellite is a space astronomical mission developed by ESA, launched in May 2009, with as scientific primary goal the study of the Cosmic Microwave Background (CMB) anisotropies: the Big Bang relic radiation. Its two instruments, High Frequency Instrument (HFI) and Low Frequency Instrument (LFI), have made an all-sky survey from centimeter to sub-millimeter wavelengths, during more than 3 years, covering about five times the whole sky area at a resolution of 5 to 30 arcmin.

While the CMB radiation, with a temperature of 2.75 K, is very isotropic and homogeneous on the sky, a 1E-5 relative accuracy is required to map the CMB anisotropy fluctuations. The 54 sub-millimeter bolometer detectors of the HFI instrument were cooled at 0.1K and associated to an electronic readout chain presenting an unprecedentedly low noise level to reach such a requirement. Unfortunately the Analog to Digital Converters (ADC) was not properly characterized on ground. This critical component, added nonlinear effect up to 2% of the primary signal fluctuations while a goal of 0.01% bias level had to be achieved to reach the most challenging science analyses in temperature and polarization at large angular scales. I will present how we have performed inflight characterization of the ADC nonlinear response at very high accuracy. This has been achieved in two steps. A ground campaign on spare chips allowed us to build constraints on the generic design of the ADC response. Then a specific inflight acquisition campaign has been designed to gather data for chips characterization. There were 54 channels with individual ADC chip and as many different nonlinear response.

I will describe the several problematics interacting with the nonlinear response and making its correction very difficult. First, the science telemetry sent to Earth consists in a sum of 40 samples over each half-period of raw signal and singularly affected by the nonlinear response of the ADC. Its correction then requires an accurate modeling of the electronic response of the detectors at high sampling. Second, the most problematic effect comes from the 4 Kelvin cooler stage which consist in a mechanical 40Hz coupled pair of compressors leaking signal on the acquired data. This spurious signals varying on a minute basis, is entangled with detector response and is only sampled at the low telemetry rate. This makes the reconstruction of all components of the signal extremely difficult. I will show how we proceed to overcome these major issues and produce the best correction of the ADC systematics, which allowed us to reach the main science goals.

While ADC nonlinearity is a usual systematic effect, I will discuss how to optimize the technical design of the readout electronics in order to avoid such similar issues for future experiments, taking into account all interdependent parameters of the global architecture of the upcoming high sensitivity CMB experiments, such as CORE+, or LiteBIRD.

9914-100, Session PThu4

A zero-bias ultrasensitive far-IR hot-electron bolometer with large dynamic range

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As more powerful instruments are being planned for the next generation of submillimeter telescopes (e.g., the Far-IR Suveyor mission), the need for better detectors is becoming more urgent. Several advanced concepts have been pursued in the recent years with the goal to achieve a detector Noise Equivalent Power (NEP) of the order of 1E-20 - 1E-19 W/sqrt(Hz) that corresponds to the photon noise limited operation of the future space borne far-IR spectrometers under an optical load ~ 1E-19 W. Our recent work was focusing on the hot-electron nanobolometer (nano-HEB), a Transition-Edge Sensor (TES) where a very low thermal conductance was achieved due to the weak electron-phonon (e-ph) coupling in a micron- or submicron-size device. Using this approach, the targeted low NEP values have been confirmed recently via direct optical measurements. The kinetic inductance detector and the quantum capacitance detector demonstrated recently a similar sensitivity.

We see nevertheless the possibility to advance the state-of-the-art even further. Increase of the operating temperature and the saturation power, and simplification of the array architecture are believed to be the important areas of improvement not only for the ultrasensitive detectors but also for far-IR detectors intended for use in photometers and polarimeters where the background is higher (NEP = 1E-18 - 1E-16 W/sqrt(Hz)). Our recent paper (Karasik et al, IEEE Trans. THz Sci.&Technol. 5, 16 (2015)) analyzed the sensitivity of a normal metal nano-HEB, which uses the Johnson Noise Thermometry (JNT) to read an increase of the electron temperature caused by the absorbed far-IR radiation. Such a detector does not require any bias lines and just needs to be connected to a low-noise microwave amplifier (LNA) via a narrowband filter defining the noise bandwidth. By using a filter bank channelizer, a ~ 1000 detectors can be multiplexed using a single amplifier. The use of normal metal eliminates the need in detector material development (like, e.g., for TES) and provide a ~100 dB dynamic range. The NEP depends on the noise temperature of the readout amplifier and is not very sensitive the e-p coupling strength. An NEP < 1E-19 W/sqrt(Hz) can be achieved with commercially available LNA.

In this paper, we will present an initial experimental study of a normal metal HEB made from a 1-square-micron normal metal patch coupled to a planar twin-slot microantenna. A SQUID-rf LNA with the noise temperature Ta < 1 K followed by a HEMT LNA with Ta ≈ 5 K and a large gain are for readout. Electrical NEP is measured by sending a dc current through the device and measuring a change of output noise power caused by the heating. At 50 mK, the NEP is ~ 1E-19 W/sqrt(Hz). The data are obtained as function of bath temperature and the filter passband and compared with the model. An on-going effort to design a 1000-element bank of narrowband (few MHz) filters needed to array multiplexing will be presented too. We will also discuss various options of LNA (HEMT, parametric superconducting amplifiers, etc.) and associated sensitivity and dynamic range trade-offs.

9914-107, Session PThu4

Developments towards the terahertz intensity interferometry

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High angular resolution is one of the key demand in modern astronomy. Recently VLTI and ALMA successfully demonstrated their capability for high angular resolution in optical and radio astronomy, respectively, while high angular resolution observation at terahertz wavelengths are yet to be realized. In order to fill this “terahertz gap”, we are considering a terahertz intensity interferometer to realize high angular resolution, which may be deployed either with ground based telescopes or space-borne missions. The presentation will discuss the concept of terahertz intensity interferometry, as well as its sensitivity, and the progress of necessary technical developments.

Intensity interferometer for astronomy observation was first realized by Hanbury-Brown and Twiss, where they successfully determined the radius of compact objects, however synthesis imaging was not possible due to the absence of the delay information at that time. We have introduced a new method to determine the delay time by making use of the intensity fluctuation, or photon bunches, governed by Bose-Einstein statistics. This new method makes synthesis imaging possible even with intensity interferometers, where direct detectors may be applied, instead of heterodyne receivers, to gain the sensitivity. Recently we have demonstrated this method at 17 GHz with Nobeyama Radioheliograph (NoRH), where we have successfully determined the delay within 5 ps, even with the electromagnetic phase information being smeared out from the signal time stream. The key to the success was the capability to fast sample the time stream data with 1.25 GS/s.

Following this success, we started to study the possibility to expand this method into terahertz region. Current developments are focused on the detector and the readout circuit. Considering a typical case of observing a 1 Jy source with a 10-m telescope at 1 THz and 100 GHz bandwidth, approximately 100 M photons/s is expected; the detector is required to respond as fast as 1 GHz or to realize NEP<10^(-17) W/Hz^(1/2). This can be achieved by an SIS photon detector with low leakage current of 1 pA, while other direct detection techniques such as TES or KIDs are too slow for this purpose. The SIS photon detector with Nb/Al/AlOx/Al/Nb is being developed to meet this specification. Preliminary results indicate that this goal would be achievable by realizing a small junction as 1 um x 1 um. Another key development is the cryogenic readout circuit, especially the first stage amplifier. This involves some specific requirements, such as gate capacitance as small as 1 fF, gate leakage current less than 1 pA, or electrical bandwidth larger than 1 GHz. The readout electronics is expected to operate at cryogenic temperature, since it should be mounted close to the SIS detector operating at 0.8 K. For this, we expect JPHEMT (Junction Pseudomorphic High Electron Mobility Transistor) to provide a breakthrough for the first stage FET.

The basic concept of terahertz intensity interferometer, details of the design and the results from the latest evaluation experiment will be presented in the talk.

9914-102, Session PThu5

A full circuit model and hybrid simulation scheme for SuperSpec filter bank spectrometers

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SuperSpec is a novel spectrometer technology designed to provide the requisite resolution (R ~ 100-500), bandwidth (~1.65:1), and sensitivity

(<10^-17 W/sqrt(Hz)) to investigate star formation and galaxy evolution during the Epoch of Reionization. Since much of the optical and ultraviolet light emitted by stars and black holes throughout the history of the universe has been absorbed and reradiated by interstellar dust, understanding star formation and galaxy evolution requires precise observations in the mm and submm regimes, which are unaffected by dust obscuration. Spectroscopic measurements are especially useful because atomic and molecular lines, such as the 158 um [CII] line, provide powerful probes for interstellar medium physics. Existing grating spectrometers and heterodyne interferometers are well-suited for studying small numbers of individual galaxies, but respectively lack the architecture and bandwidth required to conduct broadband spectral surveys over large areas of the sky.

SuperSpec integrates a broadband transmission line filter bank and hundreds of kinetic inductance detectors (KIDs) on a single chip only a few square cm in size, enabling construction of multi-pixel, focal-plane spectrometer arrays. Covering an instantaneous bandwidth of 50% or more in the 100-500 GHz range, each filter bank is comprised of a series of spectral channels realized in superconducting half-wave resonant filters coupled to a main transmission line. Each channel is terminated by a KID and the channel's spectral resolution R is equal to the quality factor Q of the loaded resonator.

Currently, our main goal is to deploy an on-sky demonstrator instrument employing this technology on a major ground-based telescope in 2017. While initial modeling has enabled a basic demonstration of the resonator operation and detector sensitivity, developing an optimized filter bank for scientific use requires a realistic circuit simulation capability which includes higher order electromagnetic effects such as non-Lorentzian channel profiles and off-resonance standing wave patterns.

We have developed a microwave network model, which assembles a full filter bank by cascading together its constituent spectral channels and transmission lines, taking into account all internal reflections. Representing each channel as a 3-port lumped-element resonator, our model agrees with full-wave Sonnet simulations of a filter bank with 5 well-separated channels and a Nyquist-spaced, 6-channel filter bank with oversampling of three. Ongoing work to fit model spectra to measured spectra will investigate the discrepancy between design and measured resonant frequency and quality factor of each channel, fully describing filter bank behavior and informing future designs.

A science-grade filter bank requires ~100 channels, which is prohibitively memory-intensive for a full-wave simulation. To drastically reduce memory requirements for accurately simulating large filter banks, we are developing a hybrid simulation scheme, which entails performing full-wave analyses on individual channels and cascading them together using our network model. This scheme agrees with our full-wave analysis of the Nyquist-spaced, 6-channel filter bank.

9914-106, Session PThu5

Low-cost Ku band interferometer for educational purposes

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The latest discoveries on the astronomy field have been associated to the development of extremely sophisticated instruments. In the case of the radio-astronomy the instrumentation has evolved to higher processing data rates and a continuous performance improvement, in the analog and digital domain. Developing, maintaining and using such a kind of instruments, especially in the radio-astronomy field, requires to understand complex processes which are plenty of subtle details. The above has inspired the engineering and astronomy community to design low-cost instruments, which can be easily replicated by the non-scientist people who possess a basic technical background.

The final goal is to provide the means to build an affordable tool for teaching radiometry sciences. In order to give a step further in this way, we introduce a design of a basic interferometer (two elements) intended to become in a handy tool for learning the basic principles behind the interferometry technique and radiometry sciences.

The first approach to present here was made by an array of two LNBs (the same models used for satellite TV) which are especially modified in order to get the timing reference from an external oscillator. As digital back end a ROACH I board was the choice due to its flexibility and short time to get it operative, allowing us to study and prepare the technical system requirements according to the phenomenon we want to capture and present in an educational setting. A description of the instruments setup will be given, in addition of the signal diagram, the implementation details and the programmed software to process the signal coming from the ROACH board.

One of the pedagogical experiences using this tool will be the measurement of the sun's angular diameter, using these two Ku band receptor, we aim to capture the solar radiation in the 11-12Ghz frequency range, the power variations at the earth spin, with a proper phase-lock of the receptors will generate a cross-correlation power oscillation where we can obtain an approximation of the angular sun's diameter. Variables of interest in the calculation of this angular diameter is the declination of the sun (which depends on the capture date and location), the relation between maximal and minimal power within a fringe cycle.

This work also presents a survey of future works focused in enhance the instruments capabilities, as can be the measurement of the sun's temperature using known-temperature loads in the calibration process in the LNB, the characterization of the antenna beam analyzing the power trends over time in a sun observation, and the usage of basic boards for data capture and correlation with the purpose of reduce the implementation costs, enabling a broader amount of students to be in touch with science and engineering.

9914-115, Session PThu5

A 4 K FTS demonstrator for future cooled space telescopes

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The next generation of far infrared space observatories are being designed to address outstanding questions in astrophysics and cosmology, in topics ranging from the formation and evolution of galaxies in the early universe, to the formation of stars and planets in the milk way. Early missions such as IRAS, ISO and Spitzer paved the way for more sensitive telescopes such as Herschel and JWST. While these missions represent significant advances in angular resolution and sensitivity, it is widely recognized that the next generation missions will require cooled telescopes and instruments, with extremely high angular resolution and sensitivity across the full far-IR band.

One such mission, SPICA, aims to achieve an increase in sensitivity of between 10 to 100 times that of Herschel, in order to reach sky limited sensitivity between 5 and 210 μm. While the telescope aperture and thus spatial resolution will be similar to that provided by Herschel, the application of an actively cooled primary mirror will reduce the telescope photon noise by two orders of magnitude at the critical longer wavelengths. The SAFARI instrument on SPICA will provide imaging spectroscopy from 30 to 210 μm with resolving powers between 300 and 3,000. The baseline design is a cryogenic FTS operating at ~4K in order to reach the ambitious low thermal background requirements.

Another proposed mission, the Far Infrared Interferometer (FIRI), combines stellar interferometry with Fourier transform spectroscopy to provide an unprecedented combination of high spatial resolution with extremely sensitive spectroscopy between 25 and 300 μm.

The SAFARI spectrometer, and both the interferometry and spectroscopy aspects of FIRI, rely on accurate delay lines. For accurate spectroscopic phase retrieval and ghost line suppression, studies have shown that position metrology sampling accuracy better than 0.1% of the shortest wavelength is required. Meeting this requirement through optical design and the control of the linear stage is relatively simple on the ground at room temperature, but becomes a substantial challenge in space at cryogenic temperatures.

This paper presents the design, testing and performance of a demonstrator 4 K interferometer delay line operated within a cryogenic test facility, intended for testing optical components at temperatures down to 4 K and for evaluation of metrology techniques for application in future 4 K interferometer mechanisms such as those proposed for FIRI and SPICA. We have modified a commercial FTS delay line mechanism for cryogenic operation. When installed in the 4 K test facility cryostat with a multiple component blackbody calibration source and a 0.3 K detector, the system enables the evaluation of metrology options, scanning and data compression techniques, and the performance of critical optical components such as beam splitters and filters at their intended operating temperatures.

The ongoing activities at the University of Lethbridge in testing of cryogenic delay lines will prove fundamental in identifying key issues in interferometer designs such as those proposed for SPICA and FIRI. The integrated test bed also allows us to investigate the potential role for Canada in delivering a cryogenic FTS mechanism for future space missions, particularly SPICA/SAFARI.

9914-118, Session PThu5

SuperSpec: design and device testing

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SuperSpec is an on-chip spectrometer being developed for multi-object, moderate resolution (R = 100?500), large bandwidth submillimeter and millimeter survey spectroscopy of high-redshift galaxies. The heart of the SuperSpec spectrometer is a microstrip filter bank that employs kinetic inductance detectors (KIDs) to detect astrophysical radiation on each filter. KIDs are superconducting series inductor and capacitor (LC) circuits, whose inductance changes when incident radiation is absorbed. The natural multiplexability and small physical size of KIDs allow for the fabrication of a wide band spectrometer that can be lithographically patterned on only a few cm2 of silicon. We will detail some of the results of our current device designs and testing. This includes investigation into both SuperSpec's optical coupling and the device noise properties.

The first astronomical application of SuperSpec targets atomic and molecular line emission from, e.g. CII and CO in external galaxies and is designed to cover the atmospheric transmission window between 180 and 320 GHz water lines, which necessitates wideband optical coupling from free space. The main design drivers for the optical coupling are high coupling efficiency and ease of fabrication. We examine both horn coupling with waveguide-to-microstrip transitions and lens-coupled antennas with wideband microstrip baluns. Coupling efficiency and beam patterns of the systems are simulated. The design solutions are evaluated in terms of bandwidth, coupling efficiency, directivity, and complexity of fabrication.

In addition we present an analysis of the noise properties of our current prototype devices. Noise contributions for Kinetic Inductance Detectors consist of Two Level System noise (TLS), generation and recombination noise, amplifier noise, and photon noise. TLS noise is the result of atoms or groups of atoms in the dielectric substrate tunneling between energy levels, resulting in a varying capacitance in the KID. Generation-recombination noise is the result of the random thermal generation of quasiparticles, and the recombination of both thermal and optical quasiparticles into Cooper pairs. Along with these noise sources we see additional low frequency noise not explained by these components. We examine each of these noise sources, their correlation between detectors, and their dependencies on operating conditions for our current prototypes.

9914-125, Session PThu5

Measurements and analysis of optical crosstalk in a microwave kinetic inductance detector array

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In the last decades, larger and larger blank surveys have been carried out in astronomy in order to study populations of galaxies in a more statistical way and to analyze rare classes of astronomical objects. For this reason is important to develop large and fast cameras also at infrared wavelengths. For example, A-??MKID is a large sub-??millimeter camera for the APEX telescope in Chile based on the kinetic inductance technology. This camera is particularly suitable for large surveys thanks to its large field-??of-??view, its huge number of pixels and therefore highmapping speed.

9914-128, Session PThu5

A general purpose terahertz camera based on kinetic inductance detectors for commercial/industrial applications

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Kinetic inductance detectors have come into prominence in the field of far-infrared, sub-millimetre and millimetre-wave astronomy by virtue of their high sensitivity and the ease of fabrication and electronic readout of large format arrays. Beyond astronomy, there are a range of disciplines that can benefit from these advances, including biomedical sensing, process control in manufacturing, hidden object detection, security screening, etc.

In collaboration with QMC Instruments Ltd., we are developing a general purpose imaging system based on focal plane arrays of lumped element KIDs operating at terahertz frequencies. We aim to have a fully functioning and versatile camera that is ready to enter the commercial marketplace within the next two years.

Here we present our progress so far, in particular, on the design and construction of the cryogenic cooling platform and cold imaging optics system; the development and fabrication of detector array architectures suited for a range of optical bands -- including options for simultaneous multi-band observations; the development and assembly of a multiplexing

readout system based on ROACH-2 electronics; the development and testing of intuitive and simple-to-operate control software; and concepts for

9914-131, Session PThu5

Development of instrumentation for differential spectroscopic measurements for the millimeter wavelengths

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The Sunyaev-Zel'dovich (SZ) effect is a powerful tool for studying clusters of galaxies and cosmology. Large mm-wave telescopes are now routinely detecting and mapping the SZ effect in a number of clusters, measure their comptonisation parameter and use them as probes of the large-scale structure and evolution of the universe.

By using accurate simulations of observations, we show that estimates of the physical parameters of clusters obtained from multi-band SZ photometry can be significantly biased, owing to the reduced frequency coverage, to the degeneracy between the parameters and to the presence of a number of independent components larger than the number of frequencies measured. By demonstrating that low-resolution spectroscopic measurements of the SZ effect that are effective in removing the degeneracy.

We describe an imaging, efficient, differential Fourier transform spectrometer (FTS), optimized for measurements of faint brightness gradients at millimeter wavelengths.

The instrument is based on a Martin-Puplett interferometer (MPI) configuration. We combined two MPIs working synchronously to use the whole input power. In our implementation the observed sky field is divided into two halves along the meridian, and each half-field corresponds to one of the two input ports of the MPI. In this way, each detector in the FTS focal planes measures the difference in brightness between two sky pixels, symmetrically located with respect to the meridian. Exploiting the high common mode rejection of the MPI, we can measure low sky brightness gradients over a high isotropic background.

This unique feature makes the MPI an optimal zero instrument, able to detect small brightness gradients embeddend in a large common background. We investigate experimentally the common-mode rejection achievable in the MPI at mm wavelengths, and discuss the use of the instrument to measure the spectrum of cosmic microwave background (CMB) anisotropy.

9914-134, Session PThu5

Development of an R=256 μ-Spec: an integrated spectrometer for submillimeter spectroscopy

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μ-Spec is a compact submillimeter (350-700 GHz) spectrometer which uses low loss superconducting niobium microstrip transmission lines and a single-crystal silicon dielectric to integrate all of the components of a grating-analog spectrometer onto a single chip. The instrument components include a slot antenna with a silicon lens for optical coupling, a phase delay transmission line network, a parallel plate waveguide interference region, and aluminum microstrip transmission line kinetic inductance detectors (KIDs). ?-Spec provide orders of magnitude reduction in size and mass from the current state of the art and will enable high-performance spectroscopy from space for observation of IR-obscured galaxies at redshifts from z~2-8.

We have already successfully evaluated the performance of a prototype ?-Spec, with spectral resolving power, R = ?/?? = 64. Here we present our progress towards developing a higher resolution version of μ-Spec (R=256/512) which would enable the first science returns for ?-Spec in a balloon flight version of this instrument. We describe our modifications to the overall design in scaling from an R=64 to an R=256 instrument, including the operation of the spectrometer in higher order using broadband order-sorting filters, and a scaling of our KID design to achieve increased sensitivity. We also describe the path for scaling this instrument to our ultimate resolution goal of R~1500 in terms of instrument size, efficiency, and configuration.

9914-136, Session PThu5

W-band planar antennas for next generation sub-millimeter focal plane arrays

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Measurement of the B-mode polarization of the Cosmic Microwave Background remains elusive. This calls for increased instrument sensitivity and more sophisticated foreground subtraction. Due to the noise of modern day detectors, such as bolometers and KIDs, being at the fundamental photon noise limit, further increase in instrument sensitivity is achieved either by employing multi-moded components or by increasing the total detector count. In this work, the approach of increasing instrument sensitivity by increasing the number of detectors is followed. The Planck spacecraft utilized 52 detectors in its High Frequency Instrument. The demands of the next generation focal planes call for arrays consisting in excess of 1000 pixels. The scalability of feed horn coupled pixels for focal plane arrays consisting of this number of pixels is restrictive given the size, weight, and manufacturing cost associated with each pixel. In this work, two alternative pixel designs based on planar antenna technology are presented. The pixels are smaller than classic horn antennas, are more lightweight and can be mass-produced using common lithographic techniques leading to reduced manufacturing costs.

Two multichroic planar antenna designs have been developed at W-band; a seashell antenna and a sinuous antenna. Each antenna supports two sub-bands and two polarisations, leading to four detectors per pixel. This doubles the number of detectors per pixel compared to classic single-band horn antennas. The antennas will ultimately be used to feed a planar mesh lens, which will define the beam on the telescope optics. Simulation results are presented for the seashell and sinuous antennas at W-band frequencies. Measurements of scale models of each antenna have been planned.

The seashell antenna consists of four dual-slot antennas. Each slot pair is excited with a microstrip transmission line. Analysis of the antenna on a thin substrate of polypropylene shows that it has highly elliptical beams (>40%) and narrow sub-bands (<10% bandwidth). The high beam ellipticity is corrected by confining the propagation of the near-field with a metallic aperture. This aperture has been optimized to minimize the beam ellipticity in each sub band.

The sinuous antenna is printed on the underside of a cylinder of polypropylene. The thickness and diameter of this polypropylene substrate has been optimized to maximize forward gain and minimize the backlobe power. The antenna has broad -10 dB impedance bandwidth (>60%) and has moderately elliptical beam performance (between 5% to 9%). The

effects of an additional matching layer have also been investigated. The antenna demonstrates symmetric beams and broadband performance leading to the extraction of two or more sub-bands.

9914-49, Session 10

Readout of a 176 pixel FDM system for SAFARI TES arrays

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SAFARI is one of the focal-plane instruments for the Japanese/European far-IR SPICA mission proposed for the ESA M5 selection. It is based on three arrays with in total 3550 TES-based bolometers with noise-equivalent powers (NEP) of 2 E-19 W/?Hz. The arrays are operated in three wavelength bands: S-band for 30-60 μm, M-band for 60-110 μm and L-band for 110-210 μm, and have background-limited sensitivity and high efficiency. SRON is developing Frequency Domain Multiplexing (FDM) for read out of large AC biased TES arrays for both the SAFARI instrument, and the XIFU instrument on the X-ray Athena mission. In FDM for SAFARI, the TES bolometers are AC biased and readout using 24 channels. Each channel contains 160 pixels of which the resonance frequencies are defined by in-house developed cryogenic lithographic LC filters. FDM is based on the amplitude modulation of a carrier signal, which also provides the AC voltage bias, with the signal detected by the TES. To overcome the dynamic range limitations of the SQUID pre-amplifier baseband feedback (BBFB), is applied. BBFB attempts to cancel the error signal in the sum-point, at the input coil of the SQUID, by feeding back a remodulated signal to the sum-point, and therefore improving the dynamic range of the SQUID pre-amplifier.

Previously we have reported on the successful low-noise read-out of 38 bolometer TES and a detailed study on the effects of electrical crosstalk using our first iteration of a prototype of the full 160 pixel FDM experiment. Using the obtained knowledge, a second generation prototype with a 176 pixel FDM experiment is developed in which the crosstalk due to carrier leakage, mutual inductance and common impedance are minimized. The cold part of the experiment consists of a detector chip with 176 pixels with a designed NEP of 7E-19 W/?Hz and two matching LC filter chips, each of which contains 88 carefully placed high-Q resonators, with in total 176 different resonance frequencies, and a single-stage SQUID. The warm electronics consist of a low-noise amplifier (LNA) and a digital board on which the generation of the bias carriers, the demodulation of the signal and remodulation of the feedback signal are performed. Compared to the previous experiment, the effect of carrier leakage has been reduced by a factor two and the effects of mutual inductance have been removed. The common impedance has been reduced by design to 4nH, of which 3nH is from the input coil of the SQUID. This has successfully been further reduced to below 1 nH by implementing screening of the input coil. By connecting the pixels in stages, corresponding to a quarter, a half and a full array, the complexity of the experiment increased in steps, which allowed us to resolve intermediate technical issues more efficiently. Number of In this paper we will report on the results obtained with this 176 pixel FDM experiment.

9914-50, Session 10

Integrated performance of a frequency domain multiplexing readout in the SPT-3G receiver

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The South Pole Telescope third generation receiver, SPT-3G, will make extremely deep, arcminute-resolution maps of the temperature and polarization of the Cosmic Microwave Background. The SPT-3G maps will enable studies of the B-mode polarization signature, constraining primordial gravitational waves as well as the effect of massive neutrinos on structure formation in the late universe. The SPT-3G receiver will achieve exceptional sensitivity through a focal plane of sim16,000 transition-edge sensor bolometers, an order of magnitude more than the current SPT receiver. SPT-3G uses a frequency domain multiplexing (fMux) scheme to readout the focal plane, combining the signals from 64 bolometers onto a single pair of wires. The fMux readout facilitates the large number of detectors in the SPT-3G focal plane by limiting the number of wires dissipating heat on the ultracold cryogenic stage. The fMux system also allows optimized operation of each bolometer. In addition to the benefits, the fMux readout introduces new challenges into the design and operation of the receiver. The bolometers are operated at a range of frequencies up to 5 MHz, requiring control of stray reactances over an expanded bandwidth. Additionally, crosstalk between multiplexed detectors will inject large false signals into the data if not adequately mitigated. SPT-3G is scheduled to deploy to the South Pole telescope in late 2016. Here, we present the pre-deployment performance of the fMux readout system with the SPT-3G focal plane.

9914-51, Session 10

FPGA-based digital signal processing for the next generation radio astronomy instruments: ultra-pure sideband separation and polarization detection

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Field Programmable Gate Arrays (FPGAs) capacity and Analog to Digital Converters (ADCs) speed have largely increased in the last decade. Nowadays we can find one million or more logic blocks (slices) as well as several thousand arithmetic units (ALUs/DSP) available on a single FPGA chip. We can also commercially procure ADC chips reaching 10 GSPS, with 8 bits resolution or more.

This unprecedented power of computing hardware has allowed the digitalization of signal processes traditionally performed with analog components. In radio astronomy the clearest example has been the development of digital sideband separating receivers which, by replacing the IF hybrid and calibrating the system imbalances, have exhibited a sideband rejection above 40dB; this is 20 to 30 dB better than traditional analog sideband separating receivers.

In Rodriguez et al.[1], and Finger et al.[2], we have demonstrated very high digital sideband separation at 3mm and 1mm wavelengths, using laboratory setups. We here show the first implementation of such technique with a 3mm receiver integrated in a telescope, where the calibration was performed by optical injection of the test tone at the secondary mirror of the Cassegrain antenna.

We also report progress in digital polarization synthesis, particularly in the implementation of a calibrated Digital Orthomode Transducer (DOMT) based on the Morgan et al. proof of concept [3]. They showed off-line synthesis of polarization with isolation better than 40dB. We plan to implement a digital polarimeter in a real-time FPGA based (ROACH-2) platform, to show ultra-pure polarization isolation in a non-stop integrating spectrometer.

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E. Michael, R. Finger and L. Bronfman. Publications of the Astronomical Society of the Pacific, Vol. 126, pp. 380-385 (2014)

[2] Ultra-pure digital sideband separation at sub-millimeter wavelengths. R.Finger, F.P.Mena, A.Barishev, A.Khudchenko, R.Rodriguez, E.Huaracan, A.Alvear, J.Barkhof, R. Hesper, L.Bronfman. Astronomy & Astrophysics, 584, A3 (2015)

[3] Compact Orthomode Transducers Using Digital Polarization Synthesis, Morgan, M.A. ; Fisher, J.R. ; Boyd, T.A. NRAO, Charlottesville, VA, USA. Microwave Theory and Techniques, IEEE Transactions on . Vol.58, Issue. 12. P. 3666 – 3676 (2010)

9914-52, Session 10

GPU-based readout for kinetic inductance detectors

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The growth of submillimeter and far-infrared (FIR) detectors arrays beyond the thousands of pixels/channels today is limited primarily by two factors: (i) the per-detector cost, and (ii) the number of channels that can be multiplexed on a single readout. Kinetic inductance detectors (KIDs) offer a step forward in both areas, combining a simple low-cost lithographic process with high multiplexing density in frequency domain. KIDs are therefore well-positioned to meet the needs of the next-generation large FIR arrays, on the ground and in space, with 100k or more pixels/channels, at low (below $1 per pixel/channel) cost. KIDs can also be used as fast optical or X-ray detectors, enabling time-resolved optical/X-ray imaging in photon-counting mode.

However, the optimal extraction of signals from a large number of frequency-multiplexed KIDs remains a challenge. Most current readout systems use FPGAs and rely on a tone-based readout approach, in which each KID resonator is excited by one or more fixed-placed tones. Changes (e.g. frequency shifts) in the detector response are characterized by those select tones alone.

We present an alternative readout system that uses commercial components (ADCs and DACs) and a graphical processing unit (GPU) to process up to 125 MHz full bandwidth instantaneously. We use broad-band excitation of the detectors, which allows for a more complete characterization of the detector response (such as resonator frequency shift, line width, amplitude, or line-shape) in real time. Our readout does not require explicit resonance search or calibration preceding a measurement, and can keep track of resonators even when these move by much more than a line-width, with no sensitivity trade-off. The full-spectrum approach also provides faster sampling than tone-based readout. E.g. for Q~10^5 resonators in the 125--250 MHz range, sampling up to ~4 kHz rates is possible.

The GPU-based readout system was successfully demonstrated in May 2015, using the MAKO camera at the Caltech Submillimeter Observatory (CSO). Its noise performance was comparable to the ROACH-based readout system. We will report these results and will present improvements to the system we implemented since. These include a new method of targeted spectral excitation, a more optimal algorithm for the extraction of frequency shifts, and improved electronic noise performance.

Ultimately, such GPU-based resonator readout, can provide an easy-to-use, and low-cost readout solution for both KIDs, and other frequency-domain multiplexed, detectors.

9914-53, Session 10

Readout of two-kilopixel transition-edge sensor arrays for advanced ACTPol

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Advanced ACTPol is an instrument upgrade for the six-meter Atacama Cosmology Telescope (ACT) designed to measure the cosmic microwave background (CMB) temperature and polarization with arcminute-scale angular resolution. Advanced ACTPol requires a higher multiplexing factor than any previous CMB experiment to achieve its science goals by incorporating approximately two thousand transition-edge sensor (TES) bolometers into each 150 mm detector wafer. We present the implementation and testing of the Advanced ACTPol time-division multiplexing readout architecture with a 64-row multiplexing factor. This includes testing of individual multichroic detector pixels and superconducting quantum interference device (SQUID) multiplexing chips, as well as testing and optimization of the integrated readout electronics. In particular, we will describe the new automated multiplexing SQUID tuning procedure we have developed to select and optimize the thousands of SQUID parameters required to read out each Advanced ACTPol array. The multichroic detector pixels in each array use separate channels for each polarization and each of the two frequencies, such that four TESes must be read out per pixel. Challenges addressed include doubling the number of detectors per multiplexed readout channel compared to ACTPol as well as optimizing the Nyquist inductance to minimize aliasing of detector and SQUID noise.

9914-54, Session 11

The Simons Array CMB polarization experiment

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The Simons Array is a next generation cosmic microwave background (CMB) polarization experiment whose science targets are precision measurements of the B-mode polarization pattern produced both by inflation and by gravitational lensing. As a continuation and extension of the successful POLARBEAR experimental program, Simons Array will consist of three cryogenic receivers each featuring multichroic bolometer arrays mounted onto separate 3.5m telescopes. The first of these, also called POLARBEAR-2, will be the first to deploy in early 2017 and has a large diameter focal plane consisting of dual-polarization dichroic pixels sensitive at 95 GHz and 150 GHz. The focal plane of POLARBEAR-2 will utilize a total of 7,588 antenna-coupled superconducting transition edge sensor (TES) bolometers read out with SQUID amplifiers using frequency domain multiplexing techniques. The next two receivers that will make up the Simons Array will be nearly identical in overall design but will feature extended frequency capability. The combination of high sensitivity, multichroic frequency coverage and large sky area available from our mid-latitude Chilean observatory will allow Simons Array to produce high quality polarization sky maps over a wide range of angular scales and to separate out the CMB B-modes from other astrophysical sources with high fidelity. The Simons Array will constrain the inflationary B-mode signal down to a tensor-to-scalar level of $r = 0.01$ (2 sigma) and will constrain the sum of neutrino masses to 40 meV (1 sigma including foreground separation residuals) when Simons Array data is cross-correlated with galaxy surveys. We present the current status of this funded experiment, its future, and discuss its projected science return.

9914-55, Session 11

POLARBEAR-2: an instrument for CMB polarization measurements

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POLARBEAR-2 (PB-2) is a ground-based CMB polarization experiment with a large detector array that consists of 7588 dual-band antenna-coupled Al-Mn bilayer transition edge sensor (TES) bolometers for simultaneous measurements at 95 and 150 GHz. The main goal of PB-2 is to detect degree scale odd-parity (B-mode) polarization patterns. The B-mode is created by primordial gravitational waves generated during the inflation. Its discovery is a smoking gun signature of inflationary universe. The PB-2 experiment expects to achieve the sensitivity of tensor to scalar ratio, r~0.01 (95% C.L.). PB-2 also plans to measure the sub-degree scale B-mode from gravitational lensing, with that the sum of neutrino masses, ?m?, will be constrained at 90meV (68 % C.L.). The receiver will be mounted on a telescope with a ~3.5m primary mirror, corresponding to the angular resolution of 3.5 arc minutes at the 150 GHz band. The receiver is being developed in the laboratory and has been tested, and we plan to start the scientific observation from early 2017. To achieve the large field of view over 4.8 degrees with high Strehl ratios, large reimaging lenses made of high purity alumina are adopted to realize the focus tele centric over the whole 365mm-diameter focal plane. The focal plane is filled with 7 wafers. Each wafer has 271 dual linear polarized pixels sensitive in 95 GHz and 150 GHz bands. A silicon lenslet with epoxy-based two-layer anti-reflection coating is placed on each pixel. Incoming radiation is coupled with a sinuous antenna. Micro-strip filters on the pixel split the signal onto two detection bands. Intensity of each signal is detected by a TES bolometer. The entire focal plane is cooled to ~250mK by a helium sorption cooler. The signal from each bolometer is amplified by a Quantum Interference Device (SQUID) and readout by multiplexed readout system based on the digital implementation of the frequency domain technique. The increase of the number of detectors requires an increase in the multiplexing factor. Therefore the number of detectors read out per SQUID is 40 at PB-2, which is larger than 8 that is achieved at PB-1. Characterizations of the PB-2 receiver system have been carried out in the lab. First of all, we measured temperatures of the optical elements and estimated the total loading to obtain expected sensitivities. We also measured positions and shapes of the lenses to model the optical system and obtained expected optical performance. The simulated side lobe levels are -20 and -25 dB at 95 and 150 GHz. These results meet our requirements. In this talk, we explain the overview of POLARBEAR-2 experiment and results of validation tests for the large optics and detector system.

9914-56, Session 11

The Primordial Inflation Polarization Explorer (PIPER)

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The Primordial Inflation Polarization ExploreR (PIPER) is a balloon-borne telescope designed to measure polarization of the Cosmic Microwave Background (CMB) on large angular scales. It will observe at 200, 270, 350, and 600 GHz on subsequent Northern and Southern-hemisphere flights, and cover 85% of the sky. PIPER's resolution permits measurement of E and B modes to l~300, and polarization modulation and stable float environment are expected to allow constraint on CMB polarization anisotropy from reionization. The instrument resides in an LHe bucket dewar, which becomes superfluid at float. Superfluid pumps permit cooling and cryogenic operation of the modulator and optics. Helium vapor from boiloff avoids the need to use a warm vacuum window. These factors allow sensitivity limited by the sky background, and competitive B-mode sensitivity from conventional balloon flights. Ultimately 8 flights provide sensitivity to the tensor-to-scalar ratio r~0.007. PIPER will spin in azimuth with a ten-minute period, at 55 degrees off zenith. Earth's rotation allows 55% of the sky to be mapped in the nighttime segment of the flight. In the day, the scan will be limited to a 20-degree strip in the anti-solar direction. The first science flight will use two 32x40 arrays of backshort-under-grid free-space absorbers and Transition Edge Sensors. Superconducting vias connect to indium bump bonds of a NIST 2D SQUID MUX. The array is multiplexed in the time domain and read with the UBC Multi-Channel Electronics. Detectors are maintained at 100 mK with a compact Continuous Adiabatic Demagnetization Refrigerator. The PIPER instrument comprises two parallel telescopes whose polarization analyzers are offset by 45 degrees about the boresight. Each telescope measures Stokes Q and V (modulated) and I (unmodulated) in its frame using a cryogenic Variable-delay Polarization Modulator (VPM). The two telescopes together yield instantaneous sensitivity to Stokes Q and U in the instrument frame. Modulation between Stokes Q and V eliminates Q to U leakage, and Stokes V is expected to be negligible at the observed angular scales and frequencies. The VPM is the first optical element. This allows the detectors to lock in on the modulation and reject instrumental polarization and 1/f drifts of the data, facilitating recovery of large angular scales. Silicon lenses follow the reflective optics and are cut with a broadband AR metamaterial layer. The band-defining filter stack, VPM throw, and some of the AR coatings will be changed between flights to survey one of each of the four bands per flight. Use of a common detector array in all frequencies is facilitated through a backshort spacing that is optimized for science bands but is less efficient at 350 GHz and 600 GHz, where loading is higher. Additionally the fractional bandwidth is reduced, to keep detector loading ~0.5 pW. PIPER's first flight will be from the Northern hemisphere, and overlap with the CLASS survey at lower frequencies. I will describe the current status of the PIPER instrument.

9914-57, Session 11

The Cosmology Large Angular Scale Surveyor (CLASS)

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The Cosmology Large Angular Scale Surveyor (CLASS) is a four telescope array designed to detect and characterize relic primordial gravitational waves from inflation and the optical depth to reionization through a measurement of the polarized cosmic microwave background (CMB) on large angular scales. The frequency bands of the CLASS telescopes, one at 38 GHz, two at 93 GHz, and one dichroic system at 145/217 GHz, are chosen to avoid regions of high atmospheric emission and span the minimum of the polarized galactic foregrounds: synchrotron emission at lower frequencies and polarized dust emission and higher frequencies. Low noise transition edge sensor detectors and a rapid front-end polarization modulator provide a unique level of high sensitivity, stability, and control of systematics. The CLASS site, at high altitude in the Chilean Atacama

desert, allows for daily mapping of up to 70% of the sky and enables the observation of the largest angular scales. Using this combination of a broad frequency range, large sky coverage, control over systematics, and high sensitivity, CLASS will observe the reionization and recombination peaks of the CMB E- and B-mode power spectra. CLASS will make a cosmic variance limited measurement of the optical depth to reionization and will measure or place upper limits on the tensor-to-scalar ratio, r, down to a level of 0.01 (95% C.L.).

9914-58, Session 12

Development of far-IR sensors based on superconducting MgB2

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Terahertz range is rich with molecular lines important for understanding of the chemistry associated with evolution of star-forming molecular clouds. High-resolution spectroscopy of such clouds greatly relies on hot-electron superconducting bolometric (HEB) mixers. Current state-of-the-art receivers use mixer devices made from ultrathin (~ 3-5 nm) films of NbN with critical temperature ~ 9-11 K. Such mixers have been deployed on a number of ground based and suborbital (SOFIA, STO, TELIS) platforms, and have been used in HIFI instrument on the Hershel Space Observatory. Despite its good sensitivity and well-established fabrication process, the NbN HEB mixer suffers from the narrow intermediate frequency (IF) bandwidth ~ 2-4 GHz and is limited to operation at liquid Helium temperature. As an interest in high-resolution spectroscopy of high THz frequency lines (e.g., [HD] 2.68 THz, [OIII] 3.39 & 5.79 THz, [OI] 4.75 THz, [NIII] 5.23 THz, etc.) is growing the need in larger IF bandwidth becomes more pressing.

A possibility to increase both the operating temperature and the IF bandwidth of HEB mixers lies with the use of superconducting MgB2 with critical temperature of 39 K. Realization of a receiver operating at 20 K would allow for the use of relatively low-cost mechanical cryocooling in space. This would be a big impact on the cost reduction and lifetime increase of an associated space mission.

Recently, thin films of this superconductor have become achievable, which opened a door for development of various detectors. Our current work focuses on the development of practical HEB mixers using ultrathin (8-20 nm) MgB2 films. We prepare films using the Hybrid Physical-Chemical Vapor Deposition (HPCVD) process in combination with ion mill yielding high-quality ultrathin films with critical temperature ~ 37-39 K on THz-transparent SiC substrates. The combination of small film thickness, large sound velocity, high acoustic phonon transparency at the interface with the substrate, and short electron-phonon relaxation time results in an IF bandwidth ≈ 9 GHz, which has been measured in 15-nm thick HEB devices. Even larger IF bandwidth is expected in thinner (5-10 nm) films, which have been already achieved. Micron- and submicron-sized spiral-antenna coupled HEB mixers have been fabricated in order to minimize the local oscillator (LO) power requirements. Preliminary measurements yielded a double-sideband noise temperature of ≈ 2,500 K weakly dependent on temperature between 4 and 20 K. This indicates that, indeed, mixer operation may be possible using a cryogen-free cooling system. An on-going material development work focuses on achieving disordered films (but still with high critical temperature) where the intrinsic quantum efficiency is expected to be high. An additional benefit of the high resistivity will be better rf and IF impedance match of HEB devices.

We will report on experimental results to date as well as on the progress in development of a cryocooler based 4.7 THz HEB receiver using a Quantum Cascade Laser (QCL) as an LO source. We will also discuss other potential applications of MgB2 films to far-IR sensors. Promising devices include tunnel-junction mixers, kinetic inductance detectors and parametric amplifiers, and flux-flow oscillators.

9914-59, Session 12

SHASTA: a high resolution 2 THz spectroscopic imaging array 3rd generation instrument for SOFIA

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The Stratospheric Heterodyne Array System for Terahertz Astronomy (SHASTA) is a 3rd generation facility instrument for the SOFIA airborne observatory, which has been selected by NASA for an Instrument Concept Study. SHASTA will have 64 heterodyne pixels with HEB mixers cooled to 4K. Each pixel will have an individually adjustable local oscillator (LO) power to yield minimum noise temperature. The LO is based on frequency multiplication in a sequence of cascaded frequency doublers and triplers derived from a common reference oscillator. This technology is derived from successful JPL work on the Herschel HIFI instrument and has been extended for use in the submillimeter receiver of the NASA APRA balloon project, STO2 (C. Walker, Univ. of Arizona, PI).

SHASTA's 1.9-2.1 THz frequency range includes two of the most important species in the interstellar medium – ionized carbon (C+) and atomic oxygen (OI) via their fine structure lines. These will undoubtedly continue to be the targets of large mapping projects for which SOFIA's 16" angular resolution will be particularly valuable. SHASTA will also be able to observe highly-excited transitions of CO, other molecules including CH, and the potentially very interesting molecular ion HeH+. SHASTA's sensitivity and pixel count will enable mapping clouds in the Milky Way and nearby galaxies dramatically more rapidly than is now possible. Previous work with Herschel/HIFI and SOFIA GREAT show that studying C+ and other fine structure lines with high velocity resolution gives critical information about the source's location in the Milky Way and the possible effect of absorption by line of sight clouds, in addition to detailed information about the structure of the source itself. SHASTA's rapid mapping capability combined with high spectral resolution will open up important new capability of understanding how molecular clouds are formed and evolve from the more diffuse interstellar medium, and how this regulates star formation.

The array pixels will be in a close-packed 8x8 square configuration, permitting high efficiency coupling through the SOFIA optics. The local oscillator signals are produced in an 8x8 array which ends with feedhorns. The 64 LO beams are then coupled into the 64 horn/mixer pixels via a Gaussian Beam telescope and dichroic beam splitter. The frontend is cooled by a closed-cycle cooler as already proven in use by the upGREAT instrument on SOFIA. The first IF stages are cooled, and after further amplification, the signal for each pixel is sent to a digital spectrometer based on a CMOS ASCI VLSI chip being developed by JPL and UCLA. The spectrometer will cover 3 GHz bandwidth, corresponding to 480 km/s at the 1900.5 GHz frequency of C+. This is adequate for covering even the Galactic Center and nearby galaxies in a single integration. The spectrometer will have 8K spectral channels, giving a resolution of 375 kHz (0.06 km/s), more than sufficiently fine to resolve kinematic structure in the regions studied. In addition to the region from 1.9 to 2.1 THz covered in its initial configuration, SHASTA is designed to readily allow upgrades to shorter wavelengths.

9914-60, Session 12

MgB2 hot electron bolometer mixers for THz heterodyne instruments

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NbN Hot Electron Bolometer (HEB) mixers have been used for many ground, airborne, and space borne high spectral resolution instruments from below 1THz up to 5THz. With a noise temperature of below 1000K and a very low Local Oscillator (LO) power requirements (<1μW), those devices have been the best choice available. Due to bolometric nature of

HEB mixers, their gain bandwidth (as much as the noise bandwidth) is limited, and in the best case it ranges to maximum 3GHz (or 5GHz of the noise bandwidth). Such a limitation becomes very critical when either a broadband line survey is performed, or Doppler broadened lines are observed from extra galactic sources. Another limiting factor for NbN HEBs (as much as for e.g. SIS mixers) is the requirement of 4K cooling, which is mostly accomplished with LHe or with rather bulky and power consuming cryo-coolers.

Both the problem of the limited gain bandwidth and the necessity of 4K cooling can be resolved with HEB mixers made from MgB2 films where a superconducting critical temperature up to 39K is feasible. Recently, we have shown that a gain bandwidth of up to 10GHz can be reached with thin MgB2 films. Furthermore, a noise temperature of <1000K can be obtained at a 1.6 THz LO frequency. Furthermore, we demonstrated that at 14K the mixer noise temperature is <2000K which can be further improved with the proper optimization of MgB2 films.

In our presentation we will also discuss the latest results of the MgB2 HEB mixer technology, as well as on the mixer sensitivity at temperatures from 10K to 25K.

9914-61, Session 12

A 2 THz Schottky solid-state heterodyne receiver for atmospheric studies

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Both interstellar medium and planetary atmosphere are incredibly rich in molecular species with spectral rotational and vibrational signatures that lie in the 1-10 THz frequency range. The neutral atomic oxygen (OI) emissions at 2.06 THz (145.525 um) and 4.7 THz (63.184 um) are the two brightest (in terms of photon flux) emission lines in the terrestrial thermosphere and have been observed from balloon, sounding rocket and orbital platforms [1].

We will present laboratory demonstration of a heterodyne receiver for the 2.06 THz OI line, similar to our previous 1.2 THz receiver [2]. This measurement takes advantage of a Schottky diode based all solid state receiver front-end that can be deployed on a CubeSat or similar miniature platform, and will be the first 2THz all solid-state heterodyne receiver measurement at 150 K ambient temperature.

The receiver consists of a mixer pumped by a local oscillator (LO) source whose fundamental source is a fixed-frequency DRO at 38 GHz. Its output is split and amplified in two separate amplifiers, each giving over a watt of power to pump four 114 GHz triplers through two waveguide power dividers. These in turn pump four 343 GHz triplers whose output is combined into a single 40 mW signal to pump the final 1.03 THz tripler. This provides the LO signal for the subharmonically-pumped 2.06 THz mixer. The mixer used in the experiment was originally designed for the 1.8 to 2.0 THz band [3].

The design was modified to extend the frequency coverage to 2.06 THz, minimizing noise and conversion loss over a reduced 20 GHz band since the system is required to cover only the narrow OI line but with the best performance achievable. The predicted output power of the LO chain is between 1 and 3 mW at 1.03 THz at 150 K, depending strongly on the power available from the combined 343 GHz pump chains. Harmonic balance and mixer temperature simulations indicate the mixer effective DSB temperature should be about 10,000 K.

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[2] E. Schlecht, et al, "Schottky diode based 1.2 THz receivers operating at room-temperature and below for planetary atmospheric sounding" IEEE Trans. Terahertz Sci. Tech, Vol 4 , No. 6, Nov. 2014.

[3] B. Thomas et al, "Terahertz cooled sub-harmonic Schottky mixers for planetary atmospheres," 5th ESA Workshop Millimeter Wave Tech. Apps, downloaded 3/30/2015 from http://aramis.obspm.fr/~maestrini/Work/Publications_files/5th_ESA_workshop_Thomas.pdf

9914-62, Session 13

CryoPAF4: a cryogenic phased array feed

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For earth- and space-based astronomical telescopes, the microwave (1-10 GHz) and millimeter-wave (10-300 GHz) frequency ranges contribute a wealth of information inaccessible at optical frequencies. There is a drive for wider bandwidths and larger fields of view without compromising the stringent sensitivity required to detect farther and fainter sources, pushing antenna and receiver technology to extreme limits.

Currently microwave/millimeter telescopes with mature cryogenic single pixel receivers have been upgraded to multi-pixel receivers and phased array feeds (PAFs) to increase effective field of view and in turn, imaging speeds. The Square Kilometer Array (SKA) has fostered early research and development of room temperature L-band (1-2 GHz) PAFs at DRAO (Canada), ASKAP (Australia) and at ASTRON (Netherlands) with system temperatures in the 40-70K range. However to attain superlative performance as compared to a single pixel feed, cryogenically cooling part or all of the front end is essential to match the high level of sensitivity possible with large reflector diameters and very low system temperatures. Cryogenic PAF research at L-band with AOPAF (Cornell U.-Arecibo) and NRAO/BYU's warm dipole and cooled LNA system have achieved 36K and 45K system temperatures respectively.

We propose a 2.8 – 5.18 GHz dual polarization coherent PAF receiver with cryogenically cooled antennas and amplifiers, to demonstrate the feasibility of sub-20K system temperatures to compete similar noise levels of single pixel receivers but at a higher frequency than current cryogenic PAFs. The resulting increase in field of view and survey speed is a factor of ~5 compared to a single pixel receiver through the production of multiple farfield beams in the beamformer.

The PAF receiver architecture is composed of a cryostat with a 50 cm diameter composite laminate radome window/aperture. Internal to the cryostat are layers of RF transparent heat shields reflecting the infrared radiation through the radome, attenuating the thermal transfer from ambient onto the large metal antenna array elements. This antenna array is composed of 140 dual-linear Vivaldi blades configured on a square grid. The 3.5K noise temperature amplifiers and the Vivaldi blades and feeds are all cooled to 16K. Concentric thin metal cylinders at 16K, 70K and 300K provide necessary thermal insulation to the low noise amplifiers and coaxial cables leading out of the dewar. External to the cryostat for each of the 96 active receiver chains is a bandpass filter followed by a 35 dB amplifier and a digital beamformer performing direct digital 8-bit sampling, 500 MHz instantaneous frequency band selection, time-domain beamforming and array covariance matrix calculation. The 96 input RF signals form 18 dual-polarization beams; 36 in total. The expected total system temperature is 18.5K.

Planned tests on DVA-1, an offset Gregorian 15 m dual-reflector telescope located at DRAO Penticton. The half opening angle at the focus to secondary is 55 degrees with a -16 dB feed edge taper. Physical and geometrical optics modelling analysis of the focal plane array will be shown including focal plane beam placement and resulting farfield beams, overlap, and aberrations off axis.

9914-63, Session 13

Progress on SuperSpec: a broadband on-chip millimeter-wave spectrometer

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SuperSpec is a novel on-chip spectrometer we are developing for moderate resolution (R ~ 100 - 500), large bandwidth (~1.65:1) submillimeter and millimeter wavelength astronomy. Its very small size, wide spectral bandwidth, and highly multiplexed detector readout will enable construction of powerful multi-beam spectrometers for observations of high-redshift galaxies. SuperSpec will be used to search for redshifted atomic and molecular line emission, particularly that in the [CII] 158 micron fine-structure transition, which is observable from z = 5 - 9 in the 250 GHz telluric window. SuperSpec will be a pathfinder instrument for future multi-object spectrometers, which will use the [CII] and other atomic lines to rapidly measure the redshifts and ISM properties of large samples of distant galaxies.

SuperSpec employs a filterbank architecture, constructed by lithographically patterning superconducting transmission line resonators. Incoming radiation propagates down a feedline past a series of tuned half-wave resonators, which are coupled to the feedline and to power detectors with adjustable coupling strengths that determine the net filter quality factor Q, which is equal to the spectrometer resolving power R. The transmission line for both the feedline and the resonator are microstrip, consisting of superconducting Nb traces on Si substrate beneath an amorphous silicon-nitride dielectric and Nb ground plane. The signal power admitted by each resonator is dissipated in a segment of lossy meander formed from titanium nitride (TiN), breaking Cooper pairs for radiation at frequencies above the superconducting gap in the TiN film. The TiN meander is connected in parallel to an interdigitated capacitor (IDC) made from the same TiN material to form a lumped element kinetic inductance detector (KID). The KIDs operate with resonant frequencies in the 100 - 200 MHz range, and are each coupled to a coplanar waveguide readout feedline (CPW) by a small coupling capacitor.

We will present the full characterization of prototype devices operating at 180 - 280 GHz. These devices couple to free space radiation with a double-slot antenna and a hyperhemispherical lens. We use a swept coherent source along with total power detectors to measure the intrinsic spectral response and on-chip efficiency of our spectral channels. Our most recent devices include low volume KIDs with an improved responsivity, and are photon-noise limited at low optical loading. The detector NEPs are better than 10^-17 W/root(Hz), sufficient for background limited performance at R = 100 on a ground-based telescope. We employ a new method for measuring photon noise using both coherent and thermal sources of radiation to cleanly separate the contributions of shot and wave noise. This allows an estimate of the detector responsivity and the end-to-end system optical efficiency. We will detail our on-going efforts to maximize the system efficiency, and develop an on-sky demonstrator.

9914-64, Session 13

Proof of concept demonstration for coherent beam pattern measurements of KID detectors

Kristina Davis, Arizona State Univ. (United States); Andrey M. Baryshev, Willem Jellema, Stephen J. C. Yates, SRON Netherlands Institute for Space Research (Netherlands)

We present the preliminary results from the first coherent beam pattern measurement of Kinetic Inductance Detectors (KIDs). KIDs are inherently direct detectors and cannot record phase information which has previously made coherent measurements with these detectors impossible. Our testing strategy utilizes a heterodyne technique where the source signal to the LO and RF sources are split and one channel from each source is combined to create a reference signal for a data acquisition system. The reference signal triggers the start of a time series measurement of the beat frequency signal as measured by the detector. The key requirement is that the time-series record always begins at a positive zero crossing of the reference signal. Any phase offset must therefore come from the location of the scanned source within the beam of the receiver. We have tested this technique on a single pixel of an Apex Microwave KID (AMKID) test array operating at 340 GHz. The results demonstrate that the technique described here accurately measures phase and amplitude of a KID pixel. This technique will allow near-field coherent beam pattern measurements to be performed on KID detectors, which has advantages in standing wave reduction, spatial filtering, and side lobe characterization. Importantly, coherent measurements allow full characterization of astronomical instruments including their optical systems, for which a far-field measurement may be inconveniently far from the receiver to be tested in-situ.

9914-65, Session 13

A far-infrared spatial/spectral Fourier interferometry laboratory-based test bed instrument

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With the recent completion of the European Space Agency Herschel and Planck missions, as demonstrated by main post-operations support ending in 2016, there is anticipation of the next Far-Infrared space missions in both Europe, North America, Japan, and throughout the world. While FIR astrophysics was significantly advanced through the observations of Herschel and Planck, with more advances coming as the data is further analyzed, there exist two fundamental limitations in the related FIR observing technology available to present-generation FIR astrophysical instruments: observation sensitivity and spatial resolution.

Observation sensitivity is advanced through improvements in FIR detector technology as well as cooled instrument and telescope optics to reduce the deleterious effects of thermal noise on the recorded data. Although Herschel housed the largest single-dish primary mirror available given the design constraints, it's spatial resolution is similar to that of Galileo's telescope 400 years ago, albeit at much longer wavelengths.

Improvements in the spatial resolution available to astrophysical observations must come from either significantly larger telescope optics, or through the use of interferometric techniques simulating large apertures. Both of these techniques are difficult and costly on a space-based platform, and are not presently found within the next-generation of FIR instruments and observatories on the funded horizon.

We describe the current status, including preliminary design, characterization efforts, and recent progress, in the development of a spatial/spectral double Fourier laboratory-based interferometer testbed instrument within the Astronomical Instrumentation Group (AIG) laboratories at the University of Lethbridge, Canada (UL). This development is supported by Canada Research Chairs (CRC), Canada Foundation for Innovation (CFI), and the National Science and Engineering Research Council of Canada (NSERC) grants. With motivation to further progress in areas including the development of spatial/spectral interferometry observation, data processing, characterization, and analysis techniques in the Far-Infrared (FIR) region of the electromagnetic spectrum, this instrument will provide laboratory demonstration of spatial-spectral interferometry.

Component characterization efforts include the validation of the testbed instrument subsystems such as the translation stage metrology calibration, optical component performance, and detector system characteristics. Theoretical design simulation results are compared against laboratory measurements. Expected system performance characteristics are provided from both a theoretical/simulation, and experimental perspective. The astronomy long range plans of several astronomy communities have identified both cooled apertures and interferometry as two FIR roadmap priorities. This instrumentation development program is in support of these international FIR priorities.

9914-66, Session 13

Laboratory demonstration of first-generation μ-Spec: a superconducting photonic spectrometer for far-infrared astrophysics

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We are developing a highly integrated photonic spectrometer-on-chip called μ-Spec for application on space or balloon telescopes for submillimeter/THz astrophysics. All components including the detectors and optical dispersion elements are integrated into a single photonic chip that can be mass produced, and utilize a highly confined microstrip architecture that provides excellent immunity to stray radiation. We use low-loss superconducting niobium transmission lines with a 0.45 ?m single-crystal silicon dielectric to produce a synthetic grating with spectral resolution and efficiency ultimately only limited by the intrinsic loss of crystalline Si at cryogenic temperatures. The photon detectors are half-wave resonator microstrip-line KIDs with aluminum top and Nb ground plane on 0.45 μm Si. We have built laboratory demonstration versions of μ-Spec in the 400—600 GHz band with 48 optical channels that operate with resolution R=64.

We report on the optical measurements of the spectrometer channels, and on characterization of the KIDs. We successfully demonstrate end-to-end optical performance that matches the expected resolution of 64, achieve channel yield of 47 out of 48, and obtain uniform channel response. Our new devices demonstrate high contrast in overlapping adjacent channels with zero out-of-band response in the 100-800 GHz range. On the materials front for our 100 nm aluminum detectors fabricated on separate test structures we obtain high quality factor resonators with Qi ~ 0.5x10^6 (at single photon readout powers) and Qi > 2x10^6 (for medium level powers), and measure quasi-particle lifetime of order 1.0 ms. We describe measurement results and challenges to integrate these high-quality films into the full μ-Spec fabrication process, which is necessary for producing ultra-sensitive MKIDs for a space or balloon instrument.

9914-111, Session 13

Multichroic seashell and cross-slot antennas with cold electron bolometers for future CMB polarization missions

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A novel type of the “seashell” multichroic antenna is proposed for cosmology space missions [1]. This polarized slot antenna is arranged in the form of a seashell with individual slots for each frequency and each polarization. Such an arrangement gives unique opportunity for independent adjusting parameters of antenna. For each frequency band the seashell antenna contains two pairs of orthogonal slots for each polarization connected by microstrip lines (MSLs) with a bolometer in the middle for in-phase operation.

The seashell antenna gives a unique opportunity to select needed bandwidth using two options. The first option is frequency selection by Resonant Cold-Electron Bolometer (RCEB) [2] with an internal nanofilter organized by a kinetic inductance of the NbN superconducting nanostrip and a capacitance of the nanoscale SIN (Superconductor-Insulator-Normal) tunnel junction. The second option is frequency selection by resonance properties of slots with MSLs and resistive Cold-Electron Bolometer (CEB) [3]. These resonance properties were properly developed when we squeezed Lambda/2-slots to smaller size by lumped capacitances for better beam shape. Matching with MSL and bolometer is organized by choosing proper position of a feeding stub relatively to the end of the slot. One of these options of frequency selection or combination of two of them can be chosen in dependence on tasks and requirements on bandwidth selection.

A Cross-Slot Antennas with RCEBs for two frequencies in one pixel is another candidate for multichroic systems. We selected a single cross-slot antenna with two RCEBs in each slot for dual frequencies of 75 and 105 GHz. The antennais designed for coupling with a Si lens in one pixel with two orthogonal polarisations. CEBs with resonance circuits are placed in the center of slots. Preliminary frequency selection in each pixel is done by antenna and final selection is realized by RCEB.

The RCEB can be effectively used to create multiband elements that is an actual task in radioastronomy due to benefits that come from their ability to use co-located data, and problems with the dramatic increase of size of the focal plane.

Development of this system is done in scope of the ESA project on creating new concepts of multifrequency pixels for a COrE space mission [3]. These multifrequency systems could be also effectively used in new projects for detecting the primordial gravitational wave background. In particular, some uncertainty in interpretation of BICEP2 results on observation of gravitational waves [4] has been just due to absence of measurements at two frequencies, 150 GHz and 95 GHz, planned originally for this experiment.

1. The ESA Tender ESTEC ITT AO/1-7256/“Next Generation Sub-millimetre

Wave Focal Plane Array Coupling Concepts", February 2013.

2. L. S. Kuzmin. "A Resonant Cold-Electron Bolometer with a Kinetic Inductance Nanofilter", IEEE TRANS. ON TERAHERTZ SCIENCE AND TECHNOLOGY, VOL. 4, pp 314-320, (2014).

3. L.S. Kuzmin, "Cold-Electron Bolometer," in the book: BOLOMETERS, ed. A.G.U.Perera, INTECHWEB.ORG, ISBN 978-953-51-0235-9, pp. 77-106. (2012). Available: http://www.intechopen.com/books/bolometers/cold-eectron-bolometers

4. BICEP2 II: EXPERIMENT AND THREE-YEAR DATA SET. BICEP2 COLLABORATION - P. ADE, et al., arXiv:1403.4302v1 [astro-ph.CO] 17 Mar 2014.

Conference 9915: High Energy, Optical, and Infrared Detectors for Astronomy VII

Sunday - Wednesday 26–29 June 2016

Part of Proceedings of SPIE Vol. 9915 High Energy, Optical, and Infrared Detectors for Astronomy VII

9915-1, Session 1

The status of European Space Agency supported detector developments

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The European Space Agency has a very strong interest in the performance enhancement of detector arrays for future scientific and astronomy missions. Improvements in Visible and Infrared wavelengths are of particular interest and the Agency undertakes a programme of continuous development aimed at enhancing the capability of detectors in these wavebands. This paper presents the status of these detector technology development activities.

9915-2, Session 1

Detector developments at Teledyne

James W. Beletic, Teledyne Imaging Sensors (United States)

No Abstract Available

9915-3, Session 1

e2v CCD and CMOS sensors and systems designed for astronomical applications

Paul R. Jorden, Paul Jerram, e2v technologies plc (United Kingdom); Douglas Jordan, e2v technologies (UK) Ltd. (United Kingdom); Jérôme Pratlong, e2v technologies plc (United Kingdom); Mark S. Robbins, e2v technologies (UK) Ltd. (United Kingdom)

No Abstract Available

9915-4, Session 1

Selex infrared sensors for scientific applications: present and future

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Many branches of science require infrared detectors sensitive to individual photons. Applications range from low background astronomy to high speed imaging. Selex-ES Ltd in Southampton, UK, has been developing HgCdTe avalanche photodiode (APD) sensors for astronomy in collaboration with ESO since 2008 and more recently the University of Hawaii. The devices utilise MOVPE grown on low-cost GaAs substrates and in combination with a mesa device structure achieve very low dark current and near-ideal MTF. MOVPE provides the ability to grow complex HgCdTe heterostructures which have proved crucial to suppress breakdown currents and allow high avalanche gain in low background situations. A custom device called Saphira (320x256/24µm) has been developed for wavefront sensors, interferometry and transient event imaging. This device has achieved read noise as low as 0.26 electrons rms and single photon imaging with avalanche gains up to x100. It is used in the ESO Gravity program for adaptive optics and fringe tracking and has been successfully trialled on the 3m NASA IRTF, 8.2m Subaru and 60 inch Mt Palomar for lucky imaging and wavefront sensing. In future the technology offers much shorter observation times for read-noise limited instruments, particularly spectroscopy. The paper will describe the MOVPE APD technology and current performance achievements. It will also summarise the telescope deployments and laboratory measurements in the astronomy community. Plans for a larger format version of Saphira for 30m class telescope era will be outlined.

9915-5, Session 2

Technological improvements on the OGRE x-ray camera system

Matthew Lewis, Neil J. Murray, Andrew D. Holland, Daniel P. Weatherill, The Open Univ. (United Kingdom); James H. Tutt, Randall L. McEntaffer, Casey T. DeRoo, Ted B. Schultz, The Univ. of Iowa (United States); Karen Holland, XCAM Ltd. (United Kingdom)

At present half of the universes baryonic matter is missing. Some theories believe that this could be residing in intergalactic filaments which emit strongly in the X-ray regime. Present space based technology is limited when it comes to imaging at these wavelengths and so new techniques are required. The Off-Plane Grating Rocket Experiment (OGRE) aims to improve the technology readiness levels of three components by using them in a sounding rocket, hopefully encouraging their use in future missions and allowing such theories to be tested. These three components consist of a newly manufactured off-plane X-ray diffraction grating, a Wolter Type 1 mirror made using single crystal silicon, and the use of EM-CCDs to capture soft X-rays. Each of these components have been previously reviewed with OGRE being the first project to utilise them in a space mission by collecting data from the binary star system Capella, a well-known X-ray source. This paper focuses on the EM-CCDs that will be used and their optimisation with a camera purposely designed for OGRE. Tests were carried out on a prototype to determine the optimal operating voltages and clock sequences for the desired operating environment allowing efficient detections of X-rays when operated at low temperatures in a vacuum. Further tests which will need to be carried out are discussed with an emphasis on differences in the operating conditions due to the camera being mounted into a sub-orbital rocket.

9915-6, Session 2

The faint intergalactic-medium red-shifted emission balloon: future UV observations with EMCCDs

Gillian Kyne, Erika T. Hamden, Nicole R. Lingner, Patrick Morrissey, D. Christopher Martin, California Institute of Technology (United States)

We present the latest developments in our joint NASA/CNEThis project is a balloon-borne UV multi-object spectrograph, which has been designed to detect faint emission from the circumgalactic medium (CGM) around low redshift galaxies. One major change from FIREBall-1 has been the use of a delta-doped Electron Multiplying CCD (EMCCD). EMCCDs can be used in photon-counting (PC) mode to achieve extremely low readout

noise (< 1e^{-}). Our testing initially focused on reducing clock induced charge (CIC) through wave shaping and well depth optimisation with the CCD Controller for Counting Photons (CCCP). This optimisation also includes methods for reducing dark current, via cooling and substrate voltage adjustment. We will present some of our dark current results from laboratory testing. Furthermore, we will briefly present some initial results from our first set of on-sky observations using our EMCCD on the 200 inch telescope at Palomar, using the Palomar Cosmic Web Imager (PCWI) with a delta-doped EMCCD.

9915-7, Session 2

The effect of proton radiation on the EMCCD for a low Earth orbit satellite mission

Kenneth W. Smith, COM DEV Canada (Canada); Olivier Daigle, Nüvü Caméras Inc. (Canada); Alan D. Scott, Louis Piche, Danya Hudson, COM DEV Canada (Canada)

We report on the proton radiation effects on a 1k x 1k ev2 EMCCD utilized in the Nüvü EM N2 1024 camera. Radiation testing was performed at the TRIUMF Proton Irradiation Facility in Canada, where the e2v CCD201-20 EMCCD received a 105 MeV proton fluence up to 5.16E+09 protons/cm2, emulating a 10 year maximum mission in low earth orbit with nominal shielding that would be expected from a small or microsatellite. The primary space-based application is for space situational awareness (SSA), where a small telescope images faint orbiting RSOs (resident space objects) on the EMCCD, resulting in faint streaks at the photon level of signal in the images. Of particular concern is the effect of proton radiation on low level CTE, where very low level signals could be severely impaired if not lost. Although other groups have reported on the characteristics of irradiated EMCCDs, their CTE results are not portable to this application. To understand the real impact of proton irradiation the device must be tested under realistic operating conditions with representative backgrounds, clock periods, and signal levels. Testing was performed both in the laboratory and under a night sky on the ground in order to emulate a complex star background environment containing RSOs. The degradation is presented and mitigation techniques are proposed. As compared to conventional CCDs, the EMCCD with high gain allows faint and moving RSOs to be detected with a relatively small telescope aperture, at improved signal to noise ratio at high frame rates. This allows the satellite platform to take sharp images immediately upon slewing to the target without the need for complex and relatively slow attitude stabilization systems.

9915-8, Session 2

Mitigating radiation damage in EMCCDs for the WFIRST coronagraph instrument: improving charge transfer efficiency

Leon K. Harding, Richard T. Demers, Bijan Nemati, Michael E. Hoenk, Max Bryk, Michael Cherng, Pavani Peddada, Jet Propulsion Lab. (United States); Nathan L. Bush, David J. Hall, Neil J. Murray, Jason P. D. Gow, Ross Burgon, Andrew D. Holland, The Open Univ. (United Kingdom)

We have established a test laboratory at JPL where we have fully characterized the CCD201-20 EMCCD sensor, which has been base-lined for both of the WFIRST coronagraph instrument's (CGI) integral field spectrograph, and imaging sensors. We can report that it meets CGI performance requirements at beginning of life. However, the difficult challenges of the WFIRST L2 space environment must also be considered, specifically its effect on the charge transfer efficiency (CTE) of the EMCCD due to radiation damage. In order to investigate these affects, we designed and completed a two-phase radiation study of a number of CCD201-20 sensors, which were irradiated at CGI-specific cryogenic temperatures. Read noise, multiplication gain, dark current, clock induced charge and CTE were assessed, pre- and post-irradiation. Since particles such as protons, electrons and cosmic rays can cause severe degradation of such performance, techniques designed to identify and mitigate this damage must therefore be developed.

Here we present the latest results designed to improve the CTE of radiation-damaged CCD201-20 sensors from the above radiation study – specifically, displacement damage from protons and the effects of electron trapping. Since the CCD201-20 is a 2-phase device, some challenges exist when attempting to probe a full pixel within the device for the purposes of assessing damage. We outline the strategies that were used and the difficulties that were encountered. Finally, we will discuss the relevant trap species and their properties that are predicted to be present for the WFIRST-CGI devices, based on the clocking rates and timings that are being used. This discussion will include predictions from a detector performance model developed at JPL, where we have assessed how WFIRST-CGI planetary yield predictions are affected by a reduction in CTE.

9915-9, Session 3

MCT APD focal plane arrays for astronomy at CEA-LETI

Johan Rothman, Eric D. de Borniol, CEA-LETI (France); Olivier Gravrand, CEA-LETI (France) and MINATEC (France); Pierre Kern, Philippe Feautrier, Institut de Planétologie et d'Astrophysique de Grenoble (France); Olivier Boulade, CEA-IRFU (France); Jean-Baptiste Le Bouquin, Institut de Planétologie et d'Astrophysique de Grenoble (France)

HgCdTe avalanche photodiodes (MCT APDs) are of first interest for tomorrow astronomy sensing. Indeed, cooled MCT APD focal plane arrays allow for wideband (from IR to visible range) high quantum efficiencies (QE) with high APD gain (larger than 10) at reasonable reverse biases (typically below 10V, depending on cutoff wavelength). Moreover, these features are associated with low excess noise factors (around 1.2) ensuring a low degradation of the information carried out by the incoming photons. The high sensitivity and low noise associated with the APD arrays enables very high frame rates (larger than 1000 frames per second) even for low flux applications which is why they are a strong candidate for the next generation of sensors for adaptive optics (AO) and fringe tracking, in which a small number of photons is detected during short integration times. During the past few years, LETI and Sofradir have been working on such an APD focal plane array in close collaboration with astronomers from IPAG. This work led to the development of the so called RAPID detector which has been used to demonstrate 2kHz frame rates IR imaging with a close to single electron read noise using APD arrays with a cut-off wavelength around 3 μm. In the present communication we will present APD gain and dark current noise characteristics obtained on detector arrays with shorter (2.5 μm) and longer (3.7 μm) cut-off wavelengths, hybridized with the RAPID ROIC and with low noise source follower (SFD) ROIC. The results will be discussed with the perspective of using these detectors in other applications such as very low flux (2.5 μm arrays) and mid IR spectroscopy (3.7 μm arrays).

9915-10, Session 3

Development activities on NIR large format MCT detectors for astrophysics and space science at CEA/SOFRADIR

Olivier Boulade, Vincent Moreau, Patrick Mulet, Pierre

Castelein, Cyril Cervera, Olivier Gravrand, Jean-Paul Zanatta, Commissariat à l'Énergie Atomique (France); Philippe Chorier, Bruno Fièque, SOFRADIR (France)

CEA and SOFRADIR have been manufacturing and characterizing near infrared detectors in the frame of ESA's Near Infrared Large Format Sensor Array roadmap to develop a 2Kx2K large format low flux low noise device for space applications such as astrophysics. These detectors use HgCdTe as the absorbing material and p/n diode technology. The technological developments (photovoltaic technology, readout circuit, ...) are shared between CEA/LETI and SOFRADIR, both in Grenoble, while most of the performances are evaluated at CEA/IRFU in Saclay where a dedicated test facility has been developed, in particular to measure very low dark currents. The paper will present the current status of these developments at the end of ESA's NIRLFSA phase 2. The performances of the latest batch of devices meet or are very close to all the requirements (quantum efficiency, dark current, cross talk, readout noise, ...) even though a glow induced by the ROIC prevents the accurate measurement of the dark current. The current devices are fairly small, 640x512 15µm pixels, and the next phase of activity will target the development of a full size 2Kx2K detector. From the design and development, to the manufacturing and finally the testing, that type of detector requests a high level of mastering. An appropriate manufacturing and process chain compatible with such a size is needed at industrial level and results obtained with CEA technology coupled with Sofradir industrial experience and work on large dimension detector allow French actors to be confident to address this type of future missions.

9915-11, Session 3

Candidate 10 micron HgCdTe arrays for the NEOCam space mission

Craig W. McMurtry, William J. Forrest, Judith L. Pipher, Meghan L. Dorn, Mario S. Cabrera, Univ. of Rochester (United States); Donald L. Lee, James W. Beletic, Chi-Yi A. Chen, Dennis D. Edwall, Teledyne Imaging Sensors (United States); Amanda K. Mainzer, Jet Propulsion Lab. (United States)

The Near Earth Object Camera (NEOCam, Mainzer et al. 2015 is one of five NASA Discovery Class mission experiments selected for Phase A: down-select to one or two experiments will take place late in 2016. NEOCam will survey the sky in search of asteroids and comets, particularly those close to the Earth's orbit. The NEOCam infrared telescope will have two infrared (IR) cameras; one covering 3 to 5 microns, and one covering 6-10 microns. Both IR cameras will use multiple 2Kx2K pixel format HAWAII-2RG arrays with different cutoff wavelength HgCdTe detectors from Teledyne Imaging Sensors. Past development work by the University of Rochester with Teledyne Imaging Sensors and JPL (McMurtry et al. 2013, Dorn et al. 2016) focused upon bringing the 10 micron HgCdTe detector technology up to NASA TRL 6+ while simultaneously meeting the requirements of NEOCam. This work extends that development program to push the format from 1Kx1K to the larger 2Kx2K pixel array. We present results on the first candidate 10 micron cutoff HgCdTe arrays, where we measured the dark current, read noise, total noise, and quantum efficiency.

9915-12, Session 3

13 micron cutoff HgCdTe detector arrays for space- and ground-based astronomy

William J. Forrest, Craig W. McMurtry, Univ. of Rochester (United States); Donald L. Lee, James W. Beletic, Teledyne Imaging Sensors (United States); Mario S. Cabrera, Univ. of Rochester (United States); Chi-Yi A. Chen, Teledyne Imaging Sensors (United States); Meghan L. Dorn, Univ. of Rochester (United States); Dennis D. Edwall, Teledyne Imaging Sensors (United States); Amanda K. Mainzer, Jet Propulsion Lab. (United States); Judith L. Pipher, Univ. of Rochester (United States)

With the recent success of our development of 10 micron HgCdTe infrared (IR) detector arrays (McMurtry et al. 2013, Girard et al. 2014, Dorn et al. 2016), we have used what we learned and extended the cutoff wavelength to 13 microns. These 13 micron HgCdTe detector arrays can operate at higher temperatures than Si:As, e.g. in a properly designed spacecraft with passive cooling, the 13 micron IR array will work well at temperatures around 30K. We present the initial measurements of dark current, noise and quantum efficiency for the first deliveries of 13 micron HgCdTe detector arrays from Teledyne Imaging Sensors. We also discuss our plans to develop 15 micron cutoff HgCdTe detector arrays which would facilitate the detection of the broad CO2 absorption feature in the atmospheres of exoplanets, particularly those in the habitable zone of their host star.

9915-13, Session 3

Performance of science-grade HgCdTe H4RG-15 image sensors

Majid Zandian, Teledyne Imaging Sensors (United States)

We present the test results of science grade substrate-removed 4K?4K HgCdTe H4RG-15 NIR 1.7 micron and SWIR 2.5 microns sensor chip assemblies (SCAs). Teledyne's 4K?4K, 15 ?m pixel infrared array, which was developed for the era of Extremely Large Telescopes, is first being used in new instrumentation on existing telescopes. We report the data on H4RG-15 arrays that have achieved science grade performance: very low dark current (<0.01 e-/pixel/sec), high quantum efficiency (70-80%), single CDS readout noise <18 e-, operability >99%, total crosstalk <2%, well capacity >75 ke-, and power dissipation less than 4 mW. These SCAs are substrate-removed HgCdTe which simultaneously detects visible and infrared light, enabling spectrographs to use a single SCA for Visible-IR sensitivity. Larger focal plane arrays can be constructed by assembling mosaics of individual arrays.

SCA 18315

Array format 4098 x 4096

Read-out integrated circuit (ROIC) H4RG-15

Power Dissipation: 3.05 mW

Cutoff wavelength (50% of peak QE): 1.79 micron

Mean Quantum Efficiency (QE) at 1,500 nm @ 110 K: 76.7 %

Median Dark current @ 0.3 V bias and 110 K: 0.0056 e-/s/pixel

Median Readout Noise, (CDS) at 100 kHz pixel readout rate: 17.8 e-

Well Capacity at 0.3 V bias: 79400 e-

Crosstalk including optical and electrical components: 1.1 %

Operability: 99.1 %

Cluster: 50 or more contiguous inoperable pixels: 0.11%

9915-14, Session 3

Mitigation of image persistence in a HAWAII2-RG by illumination

Brian McLeod, Harvard-Smithsonian Ctr. for Astrophysics (United States); Roger M. Smith, California Institute of Technology (United States)

Residual charge generation, or image persistence, in infrared detectors is a problem that affects many low-light astronomical instruments. The HAWAII-2RG in the MMT & Magellan Infrared Spectrograph shows significant persistence when first powered up. We describe here how we reduce the persistence sensitivity of this detector by exposure to light.

9915-20, Session 3

Random telegraph signal (RTS) and other anomalies in the near-infrared detector systems for the Euclid mission

Ralf Kohley, European Space Astronomy Ctr. (Spain); Rémi Barbier, Bogna Kubik, Institut de Physique Nucléaire de Lyon (France); Jean Claude Clemens, Anne Ealet, Aurélia Secroun, Ctr. de Physique des Particules de Marseille (France); Luca Conversi, European Space Astronomy Ctr. (Spain)

Euclid is an ESA mission to map the geometry of the dark Universe with a planned launch date in 2020. Euclid is optimised for two primary cosmological probes, weak gravitational lensing and baryonic acoustic oscillations. They are implemented through two science instruments on-board Euclid, a visible imager (VIS) and a near-infrared photometer and spectrometer (NISP), which are being developed and build by the Euclid Consortium instrument development teams. The NISP instrument contains a large focal plane assembly of 16 Teledyne HgCdTe H2RG detectors with 2.3 μm cut-off wavelength and SIDECAR readout electronics. The performance of the detector systems is critical to the science return of the mission and extended on-ground tests are being performed for characterisation and calibration purposes. Special attention is given also to effects even on the scale of individual pixels, which are difficult to model and calibrate, together with the identification of any possible impact on science performance.

Based on initial on-ground test results from demonstrator model detector systems, this paper discusses a variety of undesired pixel behaviour including the known effect of random telegraph signal (RTS). Stability aspects of pixel populations under changing operating conditions are addressed as well.

9915-15, Session 4

A study of the silicon divacancy in n n-channel CCDs

Daniel Wood, David J. Hall, Jason P. D. Gow, Neil J. Murray, The Open Univ. (United Kingdom); Peter Turner, e2v technologies plc (United Kingdom); Andrew D. Holland, The Open Univ. (United Kingdom)

The increasingly demanding science goals of off-ground imaging systems require exceptional charge transfer performance from the responsible image sensor, often a charge coupled device (CCD). This places importance on detailed knowledge of radiation induced charge-trapping defects within the silicon lattice of a CCD, which can degrade performance and reduce the useful lifetime of a detector. For a large range of operational temperatures and conditions, the silicon divacancy is expected to be a dominant charge-trapping defect in n-channel CCDs. This paper describes a study of the silicon divacancy in an n-channel e2v CCD 47-10 after proton irradiation to a 10 MeV equivalent fluence of 2.5?10^9 protons.cm-2. The method of trap pumping is used to analyse the defect time constants and trapping efficiencies across a broad temperature range, which are studied in the context of charge-transfer performance measurements.

9915-16, Session 4

Mapping radiation-induced defects in CCDs through space and time

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The Charge Coupled Device (CCD) has long been the detector of choice for many space-based applications. The CCD converts the signal X-rays or visible light into electrons (n-channel devices) or holes (p-channel devices) which are stored in the pixel structure during integration until the subsequent transfer of the charge packets through the device to be read out. The transfer of this signal charge is, however, not a perfect process.

Throughout the lifetime of a space-based mission the detector will be bombarded by high-energy particles and gamma rays. As time progresses, the radiation will damage the detectors, causing the Charge Transfer Efficiency (CTE) to decrease due to the creation of defects or “traps” in the silicon lattice of the detector. The defects create additional energy levels between the valence and conduction band in the silicon of the detector and electrons or holes (for n-channel or p-channel devices respectively) that pass over the defect sites may be trapped. The trapped electrons or holes will later be emitted from the traps, subject to an emission-time constant related to the energy level of the associated defect. The capture and emission of charge from the signal leads a characteristic trailing or “smearing” of images that must be corrected to enable the science goals of a mission to be met.

Over the past few years, great strides have been taken in the development of the pocket-pumping (or strictly-speaking “trap-pumping”) technique. This technique not only allows individual defects (or traps) within the device to be located to the sub-pixel level, but it enables the investigation of the trap parameters such as the emission time constant to new levels of accuracy. Recent publications have shown the power of this technique in characterizing a variety of different defects in both n- and p-channel devices and the potential for use in correction techniques, however, we are now exploring not only the trap locations and properties but the life cycle of these traps through time after irradiation. In orbit, most devices will be operating cold to suppress dark current and the devices are therefore cold whilst undergoing damage from the radiation environment. The mobility of defects varies as a function of temperature such that the mix of defects present following a cryogenic irradiation may vary significantly from that found following a room temperature irradiation or after annealing. It is therefore essential to study the trap formation and migration in orbit-like conditions and over longer timescales.

In this paper we present a selection of the latest methods and results in the trap pumping of n- and p-channel devices and demonstrate how this technique now allows us to map the radiation-induced defects in CCDs through both space and time.

9915-17, Session 4

Radiation effects on Gaia CCDs after 30 months at L2

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Since the launch of ESA’s Gaia satellite in December 2013 the 106 large-format scientific CCDs onboard have been exposed to the

radiation environment at L2. Due to a combination of the high-precision measurement requirements of the mission and the predicted proton fluxes, the effect of non-ionising radiation damage on the detectors was early identified pre-launch as potentially being a limiting factor for end-of-life scientific performance.

A number of Charge Transfer Inefficiency (CTI)-mitigation techniques have been implemented at the hardware level. These include, for example, the periodic injection of lines of charge in order to fill traps and reset the illumination history. Additionally, a supplementary buried channel was included in the pixel architecture in order to funnel small charge packets into a smaller silicon volume to reduce the number of radiation-induced traps encountered at low signal levels. An analysis of the temporal behaviour of the periodic charge injection features (both First Pixel Response and charge trails), in particular, provides a useful means of tracking the evolution of the CTI. As well as mitigation and diagnostic functionality, it also provides a platform for the comparison with similar diagnostics obtained from onground data on irradiated devices.

There is an extensive onground dataset consisting of data obtained from Gaia flight-model and engineering-model CCDs which were irradiated to known proton fluences. These datasets are used to compare the pre-flight CTI predictions to results from in-flight measurements. We also take advantage of the occasional controlled payload heating events (performed for decontamination purposes) to examine the temperature effect on the diagnostics and compare these to model predictions as well as to similarly-obtained onground results.

Despite the fact that earth-directed solar activity has been relatively low since launch, and radiation damage (so far) is less than originally feared, there are clear cases of correlation between earth-directed solar coronal mass ejection events and changes in CTI. We pay particular attention to these events and use onboard cosmic ray detection counters, solar proton data from other satellites and spacecraft spin-phase information to help examine their effects on CTI and disentangle the effects of incident proton energies and differential spacecraft shielding. A comparison of the effects on the two main types of CCD (16 micron thick standard silicon devices and 40 micron thick, high-resistivity red-enhanced devices) on the focal plane is also performed. Radiation-induced CTI in the CCD serial registers and effects of ionising radiation on the operating points of the devices are also addressed.

9915-18, Session 4

Charge transfer efficiency in a p-channel CCD irradiated cryogenically and the impact of room temperature annealing

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It is important to understand the impact of the space radiation environment on detector performance, thereby ensuring that the optimal operating conditions are selected for use in flight. The best way to achieve this is by irradiating the device using appropriate mission operating conditions, i.e. holding the device at mission operating temperature with the device powered and clocking. This paper describes the Charge Transfer Efficiency (CTE) measurements made using an e2v technologies p-channel CCD204 irradiated using protons to the 10 MeV equivalent fluence of 1.24?109 protons.cm-2 at 153 K. The device was held at 153 K for a period of 7 days after the irradiation before being allowed up to room temperature where it was held at rest, i.e. unbiased, for twenty six hours to anneal before being cooled back to 153 K for further testing, this was followed by a further one week and three weeks of room temperature annealing each separated by further testing. A comparison to results from a previous room temperature irradiation of an n-channel CCD204 is made using assumptions of a factor of two worse CTE when irradiated under cryogenic conditions which indicate that p-channel CCDs offer improved tolerance to radiation damage when irradiated under cryogenic conditions.

9915-19, Session 4

The effect of radiation-induced traps on the WFIRST coronagraph detectors

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The WFIRST Coronagraph will the most sensitive instrument ever built for direct imaging and characterization of extra-solar planets. With a design contrast expected to be better than 1e-9 after post processing, this instrument will directly image gas giants as far in as Jupiter's orbit. Direct imaging places high demand on optical detectors, not only in noise performance, but also in the need to be resistant to traps. Since the typical scene flux is measured in milli-electrons per second, the signal collected in each practicable frame will be at most a few electrons. At such extremely small signal levels, traps and their effects on the image become extremely important. To investigate their impact on the WFIRST coronagraph mission science yield, we have constructed a detailed model of the coronagraph sensor performance in the presence of traps. Built in Matlab, this model incorporates the expected and measured trap capture and emission times and cross-sections, as well as occurrence densities after exposure to irradiation in the WFIRST space environment. The model also includes the detector architecture and operation as applicable to trapping phenomena. In this presentation we describe the model, the results, and implications on sensing performance. We conclude with a discussion of mitigation strategies.

9915-37, Session PSun

Electron multiplying CMOS imaging sensor

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The electron multiplying CCD (emCCD) imaging sensors have improved drastically the Signal over Noise Ratio (SNR) in astrophysical measurements (typically for the faintest sources or the shortest integration times). With the obvious progresses in image quality and functionalities (low noise, small pixels, high quantum efficiency, backside Illumination, through silicon via for 3D stacks, low power consumption, large scale, fast frame rate) of the CMOS Imaging Sensors (CIS), it is appealing to combine the benefit of the electron multiplication in the charge domain before charge-to-voltage conversion to the CMOS 5T or 6T current pixel architecture with pinned photodiode as sensitive volume.

The introduction of high voltage gates inside the pixel has been proposed with a non-conventional CIS technology for the first time by the Sanyo Electric Company (Shimizu et al. 2009). Recently, different emCMOS pixel structures (Fereyre et al., 2015) made in a 180nm standard CIS technology have proved their ability to multiply signal significantly during integration of photo-generated carriers with an impact ionizing coefficient of the order of 1%. A significant gain in SNR has been obtained. This proof of concept open the way for CIS towards fast and single-photon imagers similar to the emCCD, but including all the benefits from CIS such as the large scale and the windowing per multiplication gain (in order to increase the dynamic range over the full image: faintest and brightest sources at the same time). However, with this reciprocation of electron packets inside the pixel during the integration phase, a new model of the gain and Excess Noise Factor (ENF) has to be developed since the emCCD Excess Noise Factor model cannot be applied to this readout architecture.

This contribution will present first a summary of the tested pixel structures, together with the modeling of the multiplication gain and Excess Noise Factor formulation introduced in Brugière et al., 2014. We will show next how the theory of the Excess Noise Factor through a generalized Burgess variance formula can be used to measure precisely the impact ionization coefficient. Among the structures tested, we will display the results obtained with the best candidates for further developments of a full size emCMOS imaging sensor. A careful study of the different sources of charge carriers during the integration, multiplication and readout phases has been conducted and the main results will be discussed to understand the contribution of the electron multiplication to the ENF and to the SNR. To conclude this paper will discuss the potential of this low light imaging technology applied to the astrophysics field.

9915-56, Session PSun

Shutter heater system for Antarctic Bright Star Survey Telescope

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BSST is a small telescope with 30cm aperture, which is used to study extrasolar planet and will be located at Antarctic. Its field of view is wide, so it can observe many targets simultaneously, which has advantage of bright star survey. After its construction, BSST will take advantage of polar night to make observation on wide scope sky area.

The camera system in BSST is composed of two parts: a camera and a shutter system. The type of camera is Andor iKon-XL CCD camera, a custom designed model for BSST. The type of CCD sensor is CCD203-82 from E2V Technologies, which is a back-illuminated, full frame transfer sensor. The pixel size of CCD sensor is 12 μm?12 μm and the sensor is arranged as a nominally resolution of 4096?4096 array. The shutter is a mechanical one, which will run normally with the ambient temperature above 0 °C while the average temperature in Dome A is about -60°C when the polar night is coming. Therefore, a heater system is designed for the shutter including a heat-hold shutter housing, temperature sensors, heater plates, an electronic board for heater driver and temperature sensor sampling and a control software in the computer.

The titanium alloy with low thermal conductivity is used on the heat-insulation cavity which is also wrapped with insulation material to hold the heat. There are two circular heater plates are mounted on upside and downside of the cavity to heat the shutter. Two temperature sensors are installed on the cavity and the upper heater plates to measure the corresponding temperatures, respectively. A thermal drive circuit board and control software are designed to control and monitor the temperature of shutter housing. The insulation cavity can insure that the ambient temperature of the shutter is above 0 °C. The Shutter System provides power input to ensure a relatively stable temperature distribution of shutter house. A closed loop feedback control—fuzzy PID control is formed with sampling temperature of inside the insulation cavity and the surface of heating plate, driving the heater to work, which can ensure that temperature inside shutter house is within the safe work range of the shutter. A simple fuzzy control algorithm is designed to improve the control precision. The temperature accuracy is measured as ±0.1°C.

Also an operation software is designed for configuration and control shutter system which is based on the EPICS(Experimental Physics and Industrial Control System) and easy to integrated into whole control system of BSST

The shutter system is tested in a deep-cooled refrigerator whose minimum chilling temperature could be -85 °C which is near the minimum temperature in Antarctic Dome Argus. The test result shows the design can meet the requirements of BSST camera system.

9915-57, Session PSun

Scientific CCD controller for the extreme environment at Antarctic

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Scientific CCD detectors are important instruments in the field of astronomical observation for its ultrahigh quantum efficiency and ultralow readout noise. Moreover the unique geographical environment, making the Antarctica the most superior astronomical observation site. So many countries have carried out the telescope projects in Antarctica. However, all the scientific CCD cameras in the commercial area basically are based on normal temperature operating condition which have not passed the reliability tests under low temperature environment as in Antarctica. And in electronic systems, the nominal normal operating temperature ranges of commercial chips are mostly above 233K, which are not reliable under condition of Antarctica.

In this paper, we report a prototype of scientific CCD controller with low noise and low temperature design. The CCD chip we used is CCD47-20 with 1k*1k pixels.

The CCD controller includes three main part, which are low noise power board (PB), the front-end electronics (FEE) and the mother board (MB). A TEC is used to cool down the CCD chip. The TEC and CCD are installed in a vacuum chamber which connect with MB through vacuum connectors. The PB and FEE also connect with MB through proper connectors, and supply low noise biases and clocks to drive the CCD. Two pre-amplifiers are set on the MB to amplify the CCD output video signals. Then the amplified video signals are transmitted to FEE for correlated double sampling (CDS) and ADC sampling. Meanwhile, the FEE monitors the temperature of CCD and TEC for CCD cooling. The FEE also controls the shutter and monitors the temperature of the shutter for shutter temperature holding. For using in the low temperature environment, most of the chips used in the controller are industrial grade products. The chip workmanship are mainly MOS process, and chips of bipolar process are usually avoided.

The controller is small in size and easy to use. A 24V power is supplied to the PB and usb3.0 is used for transmitting data and command between the system and PC. The readout noise of system could be as low as 5e^- when the CCD is cooled down to 213K and the CCD readout speed is 100kpixs/s. We simulated the extreme low temperature environment of Antarctic to test the system, and verified that the system has the ability of long time working in the extreme low temperature environment of 213K to 193K. Moreover a shutter temperature hold system which keeps the temperature of shutter above 273K is achieved for the shutter could only work steady in temperature above 273k. The whole system has been tested in low temperature environment for long time and keeps working steadily.

9915-58, Session PSun

Back-illuminated large area frame transfer CCDs for space-based hyper-spectral imaging applications

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Standard offerings of large area, back-illuminated full frame CCD sensors are available from multiple suppliers and they continue to be commonly deployed in ground- and space-based applications. By comparison the availability of large area frame transfers CCDs is sparse, with the accompanying ~2x increase in die area no doubt being a contributing factor. Modern back-illuminated CCDs yield very high quantum efficiency in the 290 to 400 nm band, a wavelength region of great interest in space-based instruments studying atmospheric phenomenon. In fast framing (e.g. 10 – 20 Hz), space-based applications such as hyper-spectral imaging, the

use of a mechanical shutter to block incident photons during readout can prove costly and lower instrument reliability. The emergence of large area, all-digital visible CMOS sensors, with integrate while read functionality, are an alternative solution to CCDs; but, even after factoring in reduced complexity and cost of support electronics, the present cost to implement such novel sensors is prohibitive to cost constrained missions. Hence, there continues to be a niche set of applications where large area, back-illuminated frame transfer CCDs with high UV quantum efficiency, high frame rate and full well, and low noise provide an advantageous solution. To address this need a family of large area frame transfer CCDs has been developed that includes 2048 (columns) x 256 (rows) (FT4), 2048 x 512 (FT5), and 2048 x 1024 (FT6) full frame transfer CCDs; and a 2048 x 1024 (FT7) split-frame transfer CCD. Each wafer contains 4 FT4, 2 FT5, 2 FT6, and 2 FT7 die. The designs have undergone radiation and accelerated life qualification and the electro-optical performance of these CCDs over the wavelength range of 290 to 900 nm is discussed.

9915-59, Session PSun

LFA controller tests and characterisation at ESA

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ESA is developing a photon to SpaceWire system for future missions in particular M4 and on a longer term M5 missions. For this purpose, ESA has initiated the development of NIR detectors activity (the Large Format Array (L.F.A) activity) and a versatile cryogenic detector controller (the L.F.A controller activity), in Europe in preparation of future Astronomy missions. The L.F.A controller activity is a parallel contracts between Caeleste (Belgium) and IDEAS (Norway). In order to validate the performances of the LFA controller developed by Caeleste a dedicated test bench has been designed and developed at ESTEC. This publication presents the test set up and the performances validation of the first prototype of the Caeleste controller at room temperature and at cryogenic temperature. The test set up and software needed to test the HAWAII-2RG and L.F.A detectors with the L.F.A controller at cryogenic temperature will be as well presented.

9915-60, Session PSun

Low temperature performance of a commercially available InGaAs image sensor

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We report evaluation results of a commercially available InGaAs image sensor G12242-0707W manufactured by Hamamatsu Photonics K. K. The InGaAs photo diode array of the sensor sensitive between 1 ?m and 1.7 ?m wavelengths at the room temperature is hybridized on a Si CMOS circuit. Although the sensor format reported in this conference is 128 ? 128 with the 20 ?m pixel pitch, the 640 ? 512 format is also available with the same pixel circuit. Because the sensor is designed for industrial purposes used with a thermoelectric cooler, using the sensor at the low temperature to minimize the dark current is not considered. Information about the characteristics of the sensor such at the low temperature is not provided from the manufacturer. Although the sensitive wavelength of an InGaAs sensor is narrow, the availability at a lower cost compared with commonly used HgCdTe sensors for astronomy is attractive for astronomical applications such as a wide field camera which uses a lot of sensors, an instrument for a small telescope, and so on.

We tested a sample of the image sensor with our original readout electronics system with a precise 16 bit ADC. The sensor was placed on a temperature controlled stage in a vacuumed cryostat with a mechanical cooler. The sensor performance was measured at a low temperature enough to minimize the dark current. The readout noise, conversion gain, linearity, and intra-pixel response were measured at 140 K. The temperature dependence of the relative wavelength response was measured between 140 K and 300 K, and the one of the dark current was measured between 80 K and 293K.

The conversion gain obtained from photon transfer curves was 1.0 ?V/e-. The full-well was larger than 1.3E6 e- within ±1.5% linearity error. The readout noise was 60 e- calculated from pixels in a line of a frame, whereas the noise calculated from pixels over lines was 200 e-. There was a bias level variation line by line and frame by frame, which we were not able to eliminate by adjusting the clock timing and coupling capacitors. The dark current decreased to the minimum value of ~20 e-/sec at 170 K. It did not become lower at the lower temperature. The sensor had a light sensitivity between 0.90 ?m and 1.57 ?m at the temperature of 140 K. We also measured the intra-pixel response. It showed a sensitivity variation within ±3 % across several pixels, and no blind area.

We found the performance of the sensor had no serious problems except for the readout noise and the dark current. This sensor would not be suitable for the astronomical observation which requires low readout noise and dark current. It, however, becomes a choice for near infrared astronomical applications such as broadband imaging observations for which the readout noise and dark current are acceptable.

9915-61, Session PSun

Noise optimization of the source follower of a CMOS pixel using BSIM3 noise model

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CMOS imagers are becoming increasingly popular in astronomy. A very low noise level is required to observe extremely faint targets and to get high-precision flux measurements. Although CMOS technology offers many advantages over CCDs, a major bottleneck is still the read noise. To move from a CMOS sensor designed for industrial applications to one suitable for scientific applications, an improved design that optimizes the noise level is essential. Here, we study the 1/f and thermal noise performance of the source follower of a CMOS pixel in detail. We identify the relevant design parameters, and analytically study their impact on the noise level using the BSIM3v3 noise model with an enhanced model of gate capacitance of the source follower in operation region. Our detailed analysis shows the dependence of the 1/f noise on the geometrical size of the source follower is not limited to minimum channel length, compared to the classical approach to achieve the minimum 1/f noise. We derive the optimal gate dimensions (the width and the length) of the source follower that minimize the 1/f noise, and validate our results using numerical simulations. By considering the thermal noise or white noise along with 1/f noise, the total input noise of the source follower depends on the capacitor ratio CG/CFD and the drain current (Id). Here, CG is the total gate capacitance of the source follower and CFD is the total floating diffusion capacitor at the input of the source follower. We demonstrate that the optimum gate capacitance (CG) depends on the chosen bias current but ranges from CFD/3 to CFD to achieve the minimum total noise of the source follower. Numerical calculation and circuit simulation with 180nm CMOS technology are performed to validate our results.

9915-62, Session PSun

A thermal blocking filter reveals the extended red sensitivity of a 1.7 micron cutoff H2RG detector

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Infrared detectors with cutoff wavelengths of ~1.7 microns have much lower sensitivity to thermal background contamination than those with longer cutoff wavelengths. This low sensitivity reduces the need for fully cryogenic systems for YJH-band work, offering the potential for “warm-pupil” instrumentation that nonetheless reduces detected thermal background to the level of dark current. However, residual sensitivity beyond the cutoff wavelength is not well characterized, and may preclude the implementation of such warm-pupil instruments. Using a custom thermal blocking filter, we characterize the long-wavelength sensitivity tail of a 1.7 micron-cutoff H2RG array, and find evidence for sensitivity beyond the cutoff. We demonstrate the performance of our custom filter, which enables warm-pupil operation at a level previously achievable only with a combination of interference filters and specialized blocking glass. This filter enables warm-pupil NIR instrument operation, which is particularly valuable for cost-effective and efficient testing systems: it has facilitated NIR detector characterization and will enable crucial laboratory tests of laser frequency comb calibration systems and other NIR calibration sources.

9915-63, Session PSun

Caliste-SO spectral response to high x-ray photon count rate produced during bright solar flares

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On board the Solar Orbiter mission to be flown in 2018, the Spectrometer Telescope Imaging X-rays (STIX) will perform time-resolved imaging spectroscopy of solar flares in the hard X-ray range (4-150 keV) to give information about the intensity, the location and the energy of electrons accelerated in the heliosphere. The imaging technique consists in a Fourier transform based on 32 X-ray collimators, each of them with a pair of grids and a spectrometer. Caliste-SO is a hybrid CdTe detector specially designed to meet the science requirements (pixel size, spectral performance) and the technical requirements (small power and volume) of STIX. A hundred of Caliste-SO devices were produced for the STIX validation models including 32 units for the flight model. Typical energy resolution of the pixels is between 0.9 keV FWHM at 14 keV when the detector is cooled down at -20°C and biased at -300V, for a peaking time of 2 μs. The low-level threshold can be set as low as 3 keV for all the pixels.

Solar flares detection is done automatically on-board Solar Orbiter and STIX trigger could be used by other instruments. Besides the datalink on this orbit has a too low rate to be shared between the 10 instruments to get from STIX photon-photon information on-ground (time, address, amplitude of each event). As a result, amplitudes from Caliste spectrometers shall be on-board converted in energy to build histograms in energy channels. For this reason, we need to study all factors contributing to variations and evolutions of the pixel transfer function on-board the spacecraft. Several weak 133Ba calibration sources will be used to correct for long-term variations due to proton irradiation in particular. Other short-term variations cannot be recovered by on-board calibration sources and are studied before the mission launch, such as the influence of the temperature and the influence of the photon count rate. Simulations performed with an event generator and the Caliste-SO geometry predicts a pile-up fraction inferior to 1 % for 2 μs peaking time setting for the maximal count rate of 100.000 counts/s/cm2. This behavioral model was completed by experimental studies that are reported here.

The first measurement campaign consisted in placing a strong 57Co source at various distances of a Caliste-SO device to access photon rates from 300 to 15000 counts/s/pixel (photon energies from 6 to 136 keV). Effects were mainly observed on the offset values and have been explained by the ASIC design. The next measurement campaign set will consist in using an X-ray generator (photon energies below 30 keV) to see if both rate and energy deposit play a role in the evolution of the spectral transfer function. The paper will present timing and spectral analysis performed with these data sets.

9915-64, Session PSun

DCDS weighted averaging theory and development for improved noise filtering in scientific CCD applications

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Readout noise is a key factor in the performance of optical systems based on charge coupled devices (CCDs). Recent developments have shown that digital correlated double sampling (DCDS) using weighted averaging may provide a further reduction in the system readout noise. This paper describes recent advances in noise filtering using DCDS. Particular emphasis is placed on optimising weighted averaging filters to reduce 1/f noise and the characterisation of system performance when using the unsettled samples within the pixel period. Experimental results are presented and compared with theoretical predictions based on the extracted noise spectrum. The analysis provides a detailed study of the relationship between the 1/f corner frequency, the pixel frequency and weighted averaging technique in comparison with the theory of matched filters. Furthermore, the results include a comparison of the noise profile with measured and simulated noise patterns. Key system metrics, including linearity and gain stability, have been characterised and are presented to confirm the suitability of this technique for high-performance scientific applications.

9915-66, Session PSun

NUV performance of e2v large BICMOS array for CASTOR

Alan D. Scott, Alexander Beaton, Niladri Roy, COM DEV International Ltd. (Canada); Patrick Côté, John B. Hutchings, National Research Council Canada (Canada); Oleg Djazovski, Denis Laurin, Canadian Space Agency (Canada)

We have characterized the e2v CIS113 16 micron pitch 4608 x 1920 back-illuminated CMOS (BICMOS) array with near Ultraviolet (NUV) sensitization surface processing and measured its quantum efficiency over the wavelength range from 150 to 350 nm.

The Cosmological Advanced Survey Telescope for Optical and UV Research (CASTOR) is a proposed Canadian Space Agency (CSA) mission that would provide panoramic, high-resolution imaging of 1/8th of the sky in the UV/optical (150-550 nm) spectral region. This small-satellite class mission would provide high angular resolution ultra-deep imaging in three broad filters to supplement data from planned international dark energy missions (Euclid, WFIRST) as well as from the Large Synoptic Survey Telescope

(LSST). One of the leading technical risks on this mission is the UV sensitivity required to approach 26th magnitude in the near UV band.

In this paper we briefly describe the architecture of this new high speed, high sensitivity CMOS detector and report on the results of our characterization and the implications for the proposed CASTOR survey mission.

9915-67, Session PSun

Characterization of infrared APD arrays

Tim Hardy, NRC - Herzberg Institute of Astrophysics (Canada)

We present results from our testing of near infrared APD arrays from SELEX ES. We discuss the non-linear behaviour of these devices and compare to mathematical models which show good agreement with our experimental data. We also discuss some other non-ideal characteristics we have encountered. Finally, we describe a compact detector system designed as an easily deployable demonstrator for on-sky testing.

9915-68, Session PSun

The test results of signal processing ASIC for astronomical CCD system

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An astronomical CCD system ASIC (Application-Specific Integrated Circuit) development plan has started in the National Astronomical Observatories of China(NAOC). The plan is to develop universal ASICs for astronomical CCD systems, which are used for ground-based or space-based Astronomical equipment. One of projects is to develop an eight channel universal signal processing ASIC. Signal processing chain is a very important part of the CCD electronics. It is a decisive factor for the final performances of the CCD system, such as readout noise, linearity, etc.. There is a big amount of signal channels in a multi CCD system. In this case, using the signal processing ASICs will greatly reduce the size and power consumption of the system. The first prototype chips with two channel signal processing circuits have been designed and fabricated in the NAOC. The function tests and performance measurements with an e2v astronomical CCD in LN dewar have been done in the CCD lab of the NAOC. This presentation will describe the function and the performance of this ASIC chip and will report the test results.

9915-69, Session PSun

NIR camera and spectrograph SWIMS for TAO 6.5m telescope: array control system and its performance

Yasunori Terao, Kentaro Motohara, Masahiro Konishi, Hidenori Takahashi, Natsuko M. Kato, Yutaro Kitagawa, Yutaka Kobayakawa, Hirofumi Ohashi, The Univ. of Tokyo (Japan); Ken Tateuchi, East Japan Railway Co. (Japan); Soya Todo, Canon Inc. (Japan)

SWIMS (Simultaneous-color Wide-field Infrared Multi-object Spectrograph) is a near infrared imager and multi-object spectrograph as one of the first generation instruments for the University of Tokyo Atacama Observatory (TAO) 6.5m telescope. One of the advantages of SWIMS is simultaneous imaging or spectroscopy at short (0.9?1.4um) and long (1.4?2.5um) wavelength ranges in the near infrared. Incident light is split into blue and red arms by a dichroic mirror and focused onto two focal plane arrays (2k ? 2k HAWAII-2RGs) on each arm.

In this presentation, we will show a software system of SWIMS for simultaneous driving of HAWAII-2RGs and results of its performance evaluation.

HAWAII-2RG is an infrared detector developed by Teledyne Imaging Sensor (TIS). It is controlled and read out by two circuits, SIDECAR ASIC and JADE2 card. SIDECAR ASIC controls HAWAII-2RG by generating clocks to drive it, amplifying output signals and performing AD conversion. It is located near the detector and driven under cryogenic temperature with vacuum condition. JADE2 card provides power supply for SIDECAR ASIC and works as an interface board between a PC and the ASIC. It is driven under room temperature with vacuum condition and controlled by the PC via a USB 2.0 interface. In the case of SWIMS, we have fabricated special flat cables to connect SIDECAR ASICs and JADE2 cards instead of what provided by TIS as the distance between them is long (~1.7m).

We use two Linux PCs to control the detector systems on blue and red arms for simultaneous driving of the four HAWAII-2RGs. Each PC runs two virtual Windows machines on which GUI-based software runs to control JADE2 card and socket communication is performed to control them from the Linux PC. Two HAWAII-2RGs on the same arm are controlled simultaneously by a software with multi-thread process. Linux PCs are controlled by a superordinate PC which controls all systems of SWIMS through asynchronous TCP/IP communication. In this way, finally we can drive all four HAWAII-2RGs simultaneously. Whole the Linux software system is scripted by Python.

The requirement for readout noise of SWIMS is less than 14e- for background limit observations. We confirmed the readout noise to be 4.3e- r.m.s. by 32 times multisampling when we operate only single HAWAII-2RG. In the case of simultaneous driving of two HAWAII-2RGs, we got sufficiently low readout noise of 10e- r.m.s. using shielded flat cables between the SIDECAR ASIC and the JADE2 card.

9915-70, Session PSun

EMCCD camera characterization for optimal use in astronomical applications

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Electron-Multiplying Charge-Coupled Device (EMCCD) are a high favorable technology for faint photon flux sources photometry encountered in astronomy and high frame rate imaging for high spatial resolution techniques. It operates by passing the photoelectron pixel charge through a multiplication gain register before the readout process improving the signal-to-noise ratio of the image. However, some unwanted characteristics not found in conventional CCDs arise and need to be considering for optimal observations. Accordingly, in addition of the conventional methods used for CCDs like dark current analysis and Photon Transfer Curve different methods for the characterization of the EMCCD have to be performed. We present the results of the characterization of a 1004x1002 pixels EMCCD for optical wavelengths housed and controlled by the Andor iXon 885 camera for use in astronomical applications. The results provide the optimal parameters for conventional mode, analog mode and photon counting mode EMCCD operation.

9915-71, Session PSun

Characterization of H2RG IR detectors for the Euclid NISP instrument

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Euclid is a major ESA mission for the study of dark energy planned to launch in 2020. Euclid will probe the expansion history of the Universe using weak lensing and BAO probes. A survey of 15,000 deg2 of the darkest sky with NISP (Near-Infrared Spectro-Photometer), in the 900 – 2100 nm band, will give redshifts of tens of millions of galaxies. NISP's FPA will be filled with 16 of Teledyne's 2.3 μm cutoff 2048x2048 pixels H2RG infrared detectors, for which strong requirements have been derived from scientific goals. These IR HgCdTe detectors are a key element of the instrument. They must show very high performances over more than 95% of pixels, in terms of median dark current (<0.07 e-/s), total noise (<13 e-), a budget error on non-linearity after correction (<1%), residual dark due to latency effects (<0.5 e-/s after 5 hours) and quantum efficiency (>75% over the wavelength range). While NASA, who will select flight detectors under Euclid specification, will do the acceptance tests, CPPM is responsible for the characterization of the detectors performances, namely the production of the pixel map calibration database of the Focal plan for the Euclid mission.

Characterization is challenging in many ways: each detector will have to be fully and accurately characterized in 21 days. Some of the tight characterization requirements are: dark levels as low as 10^{-3} e-/s with an accuracy of 10% (Goal 5%), a relative Pixel Response map better than 1%, obtained with an illumination flatness better than 1%, measurements alternating dark and high level illumination should be implemented taking care of latency impacts on successive parameter measurements. Due to statistics needs, very long runs (24h to 48h without interrupts, ~99% of duty cycle) of scripted measurements would be executed. Systematics of the test bench should be at the end the limiting factor of the parameter measurement accuracy. Facilities with functionalities developed for those specific purposes and associated performances will be described. A pilot run with high performances detectors will verify the characterization chain from the hardware acquisitions to the analysis methods and software tools, and will validate the characterization flow down to reach the desired accuracy. First results of this pilot run will be presented that show the quality of the characterization chain, including measurements of dark/ noise, conversion gain with PTC method and non-linearity measurements. Next step will be the characterization of flight detectors expected to start in Summer 2016.

9915-72, Session PSun

Using an OLED smartphone display for in-lab microwave kinetic inductance detector illumination tests

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We present our efforts to develop a flexible smartphone based platform for in-lab optical testing of optical/near-IR detectors, namely Microwave Kinetic Inductance Detectors (MKIDs). MKIDs are a rapidly developing technology; the first 1,000-pixel UV, optical, near-IR (UVOIR) MKID array was fielded on sky in 2011, and the next generation of near-IR MKID instruments scheduled for deployment in 2016 will house 10- to 20-kilopixel arrays. As with any detector development, we require the ability to verify our MKIDs in the laboratory with various patterns and intensities of illumination across multiple wavelengths. However, previous schemes employing fiber-fed lithographic masks mounted on precision translation stages were limited by the reliability and price of these components, and did not easily scale up to accommodate testing of larger arrays. A smartphone with organic LED (OLED) displays presents a cost-effective alternative because it allows us to change projected images without needing to handle delicate glass masks, and test patterns can be moved across the detector without the need for expensive translation stages. The use of an OLED display, rather than a backlit LCD, is especially attractive as it lets us achieve true-black in images and control individual pixel brightness absolutely when generating illumination patterns. Additionally, the open-source nature of the Android operating system ensures ease of programming and readily shareable code. Here we present the opto-mechanical design of the lab setup and lessons learned while applying it to the characterization of DARKNESS, a 10-kilopixel MKID integral field spectrograph deploying to Palomar's Hale Telescope in July 2016.

9915-73, Session PSun

Evaluating noise performance of the IUCAA SIDECAR drive electronics controller (ISDEC) based system for TMT on instrument wavefront sensing (OIWFS) application

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As a part of the design study of the On-Instrument Low Order Wave-front Sensor (OIWFS) for the TMT Infra-Red Imaging Spectrograph (IRIS), we recently evaluated the noise performance of a detector control system consisting of IUCAA SIDECAR DRIVE ELECRONICS CONTROLLER (ISDEC), SIDECAR ASIC and HAWAII-2RG (H2RG) MUX. To understand and improve the performance of this system to serve as a near infrared tip tilt sensor, we implemented new read out modes like multiple region of interest with differential multi-accumulate readout schemes for the HAWAII-2RG (H2RG) detector. In this system, firmware running in SIDECAR ASIC programs the detector for ROI readout, reads the detector, processes the detector output and writes the digitized data into its internal memory. ISDEC reads the digitized data from ASIC, performs the differential multi-accumulate operations and then sends the processed data to PC over a USB interface. A special loopback board was designed and used to measure and reduce the noise from ASIC. This paper describes the methods and techniques used to measure and reduce readout noise of the system. With bias and reference filtering and co-adding, we were able to reduce the mean r.m.s. read noise of this system down to 1-2 e. for any arbitrary window frame of 4x4 size at frame rates below about 200 Hz.

9915-75, Session PSun

ESA's CCD test bench for the PLATO mission

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PLATO is a mission proposed in 2007 to the European Space Agency (ESA) in response to the call for ESA Cosmic Vision 2015–2025. The main mission goal is to find planets like Earth around solar-type stars by the transit method..The payload will consist of 34 separate small telescopes, with 4 CCDs of 4510 x 4510 pixels, at the focal plane of each of them. In support of the CCD development and characterization (the procurement of which is ESA's responsibility), the Payload Technology Validation team has built a dedicated test bench. This bench allows for a flexible operation and readout of the CCDs. It provides the basic tools for noise and gain calibration, and CTI, QE and PRNU measurements.

The bench hosts an in-house manufactured cryostat, where the CCDs can be placed in a vacuum environment and actively cooled using a Cryo-tiger. The cryostat was designed to host the PLATO CCD in its own package and handling jig to minimize handling, and is fitted with a large window for full illumination of the CCD. A python based software was developed in-house to support the bench two main functionalities the control and readout of the CCD under test, and the control, monitoring as well as safety of the CCD in its cryostat environment.

The CCD controller and readout is performed by an Archon controller (provided by Semiconductor Technology Associates). It is able to operate up to (and beyond) the PLATO CCD nominal pixel rate of 4 MHz. Among the many features of this controller one can note the use of digital correlated double sampling to measure pixel values and the possibility of defining clock slew rates. The bench software controls, on top of the CCD controller, all the elements necessary for the tests to be performed, light sources, translation stages for spot scanning etc.

The CCD operating environment must be closely controlled and monitored, in particular the temperature range and stability of the CCD under test, as this information is critical to data analysis. The temperature setting and control elements consist of a cold finger, a copper block on which the CCD within its transport jig is mounted and between these two elements, a set of straps – of which the thermal conductivity sets the temperature range at the CCD. To achieve the thermal stability of the CCD package, the thermal control loop consists of a Lakeshore controller with two heaters glued on the copper block. The PID loop temperature set-point is given by a temperature sensor placed on the copper block which gives a stable control loop, the challenge is to reach the required stability and readout accuracy at the CCD package level.

The paper will focus on the solutions implemented and the performance achieved on the thermal stability of the CCDs tested in the bench.

9915-76, Session PSun

Experiments with synchronized sCMOS cameras

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Scientific-CMOS (sCMOS) cameras can combine low noise with high readout speeds and do not suffer the charge multiplication noise that effectively reduces the quantum efficiency of electron multiplying CCDs by a factor 2. As such they have strong potential in fast photometry and polarimetry instrumentation. In this paper we describe the results of laboratory experiments using a pair of commercial sCMOS cameras based around a 4 transistor per pixel architecture. In particular we evaluate the timing precision that may be obtained in rolling and pseudo-global shutter modes both individually and when the cameras readouts are synchronized either in software or electronically. This precision is important for potential applications of these detectors to high-speed simultaneous multi-band photometry and polarimetry.

9915-77, Session PSun

A project plans to develop two ASICs for CCD control

Qian Song, Quan Sun, National Astronomical Observatories (China)

Astronomical instrumentation, in more and more cases, especially in the large field of view application while the huge mosaic of CCD or CMOS is needed, requires the controlling electronics of the camera to be much more compact and of much smaller a size than the discrete-part controller used to be. Making the major parts of CCD driving circuits into an ASIC or ASICs can greatly bring down the controller's volume, weight and power consumption and make it easier to control the crosstalk brought up by the long length of the cables connecting the controller's front end and back end, and, therefore, it's the most desirable way to build the large mosaic CCD camera. In our presentation, we will introduce our ASIC develop project that is engaged to develop two ASICs to handle with CCD signal readout and clock driver generating.

9915-78, Session PSun

IDSAC-IUCAA digital sampler array controller

Sabyasachi Chattopadhyay, Pravinkumar A. Chordia, Anamparambu N. Ramaprakash, Mahesh P. Burse, Bhushan Joshi, Kalpesh Chillal, Inter-Univ. Ctr. for Astronomy and Astrophysics (India)

In order to run the large format detector arrays and mosaics that are required by most astronomical instruments, high speed readout electronic controllers are required which can process multiple CCD outputs simultaneously at high speed and low noise. These CCD controllers needs to be modular and configurable, should be able to run multiple CCDs. IDSAC, a generic CCD Controller has been developed which is adequately flexible and powerful enough to control wide variety of CCDs used in ground based astronomy. It has a fully scalable architecture, which can control multiple CCDs and can be easily expanded. The controller has a modular backplane architecture consists of Single Board Controller Cards (SBCs) and can control a mosaic or independent of 5 CCDs. Each Single Board Controller (SBC) has all the resources to a run Single large format CCD having up to four outputs. All SBCs are identical and are easily interchangeable without any reconfiguration. A four channel video processor can process up to four output CCDs with or without dummy output at 1Mpixels/Sec/Channel with 16 bit resolution. Each SBC will have USB 2.0 interface which will be connected to a separate computer via USB to Fiber converters. The SBC uses a reconfigurable hardware (FPGA) as a Master Controller. The best feature of IDSAC is it uses the technique of Digital Correlated Double Sampling(DCDS). It is known that CCD video output is dominated by thermal KTC noise contributed from the summing well capacitor of the CCD output circuitry. To eliminate thermal KTC noise Correlated Double Sampling (CDS) is a very standard technique. CDS performed in Digital domain (DCDS) has several advantages over its analog counterpart, such as - less electronics, faster readout and easier post processing. It is also flexible with sampling rate and pixel throughput while maintaining the core circuit topology intact. The noise characterization of the IDSAC CDS signal chain has been performed by analytical modelling, software simulation and practical measurements. Various types of noise such as white, pink, power supply, bias etc. has been considered while creating a analytical noise model tool to predict noise of a controller system like IDSAC. Standard test bench softwares like Pspice and Multisim are used to simulate the noise performance while several tests are performed to measure the actual noise of IDSAC.The theoretical calculation matches very well with component level simulation as well as practical measurements within 10% accuracy.

9915-79, Session PSun

An optical test bench to measure the effective pixels positions for the HARPS3 CCD

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We present our work on an optical test bench to measure the effective pixel positions on a CCD for the high resolution (R~115,000) spectrograph HARPS3, which is a new instrument planned for the Isaac Newton Telescope (INT).

In the radial velocity (RV) technique of exoplanet detection, an Earth-mass planet produces a radial velocity signal of amplitude 0.1ms-1. On the HARPS3 4k x 4k CCD, this RV measurement corresponds to a Doppler shift in single spectral line of ~1x10-4pixel. One of the sources of systematic error in the system is in the calculation of the wavelength solution. Improvements in this wavelength calibration require a better understanding of the effective pixel positions.

In this paper we present our initial experiment design, a description of our CCD test bench, the measures we take to minimize environmental noise, and the principle and techniques used to determine the effect pixel sizes and locations to the 1x10-4px limit. We also present results from our preliminary feasibility experiments.

9915-80, Session PSun

ISDEC-2 and ISDEC-3 controllers for HAWAII detectors

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ISDEC-2 - IUCAA SIDECAR drive electronics controller is an alternative for Teledyne make JADE2 based controller. It is a ready to use complete package and has been developed keeping in mind general astronomical requirements and widely used observatory set-ups like preferred OS-Linux , multi-extensions fits output with fully populated headers (with detector as well as telescope and observation specific information), etc. Actual exposure times are measured for each frame to a few tens of microsecond accuracy and put in the fits header. It also caters to the application specific requirements like fast resets, strip mode, multiple region readout with on board co-adding, etc. ISDEC-2 is designed to work at -40 deg. and already in use at many places worldwide.

ISDEC-3 - is a Artix-7 FPGA based SIDECAR drive electronics controller currently being developed at IUCAA. It would retain all the functionality supported by ISDEC-2 and would also support the operation of H2RG in fast (32 output, 5 MSPS, 12 bit) mode. It will have 5 Gbps USB 3.0 PC interface and 1 Gbps Ethernet interface for image data transfer from SIDECAR to host PC. Additionally, the board will have DDR-3 memory for on-board storage and processing. ISDEC-3 shall be capable of handling two nos. of SIDECAR simultaneously (in sync) for H2RG slow modes.

9915-81, Session PSun

Array controller system with cryogenic pre-amplifiers for MIMIZUKU

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MIMIZUKU is a mid-IR imager and spectrograph being developed for the University of Tokyo Atacama Observatory (TAO) 6.5-m telescope (Yoshii et al. 2014). To fully utilize high atmospheric transmission of the Co. Chajnantor site, MIMIZUKU covers a wide wavelength range from 2 to 38 microns with three arrays: a HAWAII-1RG 1024x1024 detector manufactured by Teledyne (for 2-5.3 microns), an AQUARIUS 1024x1024 detector by Raytheon (for 6.8-26 microns), and a MF-128 Si:Sb 128x128 detector by DRS (for 24-38 microns). To operate and read out these various arrays, an array controller system has been developed.

The array controller system was originally developed for MF-128 Si:Sb array equipped in our previous camera MAX38 (Miyata et al. 2008; Sako et al. 2008). Some modifications have been adopted for adding the operationability of the H1RG and the AQUARIUS arrays. Three array controllers are used for MIMIZUKU in parallel, and they operate independently. This is effective to simplify the system and make debugging easy. Because thermal background is very high in the mid-infrared wavelength range, a sampling rate is needed to be higher than 0.5 MHz. Such a high speed signal is dulled while passing through a signal line from the array to the pre-amplifiers. This is very serious in the case of MIMIZUKU, because MIMIZUKU is a large-scaled complicated instrument. To overcome this problem, a high-speed pre-amplifier system operating at a cryogenic temperature has been developed. This employs GaAs-MESFETs, instead of Si-JFETs. Their cryogenic noise performances were confirmed to satisfy our requirement. This system is installed at the outer side of the optical bench in the MIMIZUKU cryostat, and cooled to 20 K.

In this paper we describe the details of the array controller system and present the current status of the development. We also report preliminary results of operation tests of the AQUARIUS array with our system.

9915-82, Session PSun

Silicon photomultipliers as readout elements for a Compton Effect polarimeter: the COMPASS project

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The measurement of the polarisation of hard X-rays by means of the Compton Effect is the scientific objective of a research and development project named COMpton Polarimeter with Avalanche Silicon readout (COMPASS). The measurement is obtained by using a set of small rods of fast scintillators of both low-Z (as active scatterer) and high-Z (as absorber), all read-out with Silicon Photomultipliers (SiPMs). By this

method we can operate scattering and absorbing elements in coincidence, in order to reduce the background.

In the laboratory we are characterising the SiPMs using different types of scintillators and we are optimising the performances in terms of energy resolution, energy threshold and photon tagging efficiency.

We aim to study the design of two types of satellite-borne instruments: a focal plane polarimeter to be coupled with multilayer optics for hard X-rays and a large area and wide field of view polarimeter for transients and Gamma Ray Bursts.

In this paper we describe the status of the COMPASS project, we report about the laboratory measurements and we describe our future perspectives.

9915-83, Session PSun

Comparing simulations and test data of a radiation damaged CCD for the Euclid mission

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The radiation damage effects from the harsh radiative environment outside the Earth's atmosphere can be a cause for concern for most space missions. With the science goals becoming ever more demanding, the requirements on the precision of the instruments on board these missions also increases, and it is therefore important to investigate how the radiation induced damage affects the Charge-Couple Devices (CCDs) that most of these instruments rely on.

In a radiative environment traps can be induces in the silicon lattice of a CCD. These traps are able to capture electrons from one charge package and release them into another charge package at a later time, thus deteriorating the charge transfer efficiency. This leads to a smearing of the image which can have a large impact on the precision of the data.

The primary goal of the Euclid mission is to study the dark universe using weak lensing and baryonic acoustic oscillation techniques. The weak lensing technique depends on very precise shape measurements of distant galaxies obtained by a large CCD array. Over the 5 year nominal lifetime of mission, the CCDs will be degraded to an extent that these measurements will not be possible unless the radiation damage effect are corrected.

In order to further our understanding of the positions and properties of the individual traps, we have created a Monte Carlo model that simulates the physical processes taking place in a radiation damaged CCD. The software is based on Shockley-Read-Hall theory, and are made to mimic the physical properties in the CCD as close as possible. The code runs on a single electrode level and takes charge cloud size and density, three dimensional trap position, and multi-level clocking into account.

This paper will present a comparison between simulations and test data obtained with the CCD273 for the Euclid mission.

9915-84, Session PSun

Simplified charge transfer inefficiency mitigation by trap pumping

Jason P. D. Gow, Neil J. Murray, The Open Univ. (United Kingdom)

The issue of radiation induced Charge Transfer Inefficiency (CTI) is the main disadvantage of using a Charge Coupled Device (CCD) in hostile radiation environments. The CTI increases as a result of defects created within the silicon lattice arising from displacement damage from radiation incident on the detector, these defects can capture and hold charge for a period of time dependant on the operating temperature and the type of defect. The location and type of defect can be determined using trap pumping, where charge is shuffled forwards and backwards between pixels using different transfer times to determine the defects emission time constant. It is also possible to move the charge forwards and backwards using the clocking scheme used to perform normal CCD readout, in this case producing a trap map of the defects which will likely impact charge loss when the device is readout. This paper describes an analytical algorithm created to investigate the ability to recover lost charge in X-ray images from a p channel CCD204, irradiated at 153 K, and assess the ability to add charge back into the X-ray event from which it was lost and report the subsequent improvement in the effective CTI.

9915-85, Session PSun

MeV-level electron and gamma ray sensitivity of modern far ultraviolet sensitive microchannel plate detectors

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The Jovian system is the focus of multiple current and future NASA and ESA missions, but dangerously high radiation levels surrounding the planet make operations of instruments sensitive to high energy electrons or gamma rays problematic. Microchannel plate (MCP) detectors have been the detectors of choice in planetary ultraviolet spectrographs for decades. However, the same properties that give these detectors high response to vacuum ultraviolet photons also make them sensitive to high energy electrons and gamma rays. The success of ultraviolet investigations in the Jovian system depends on effectively shielding these MCP detectors protecting them as much as possible from the withering radiation environment. The design of such shielding hinges on our understanding of the response of MCP detectors to the high energy electrons and gamma rays found there. To this end, Southwest Research Institute and Massachusetts Institute of Technology collaborated in 2012-13 to measure the response of a flight-spare microchannel plate detector to a beam of high energy electrons. The detector response was measured at multiple beam energies ranging from 0.5-2.5 MeV and multiple currents. This response was then checked with MCNP6, a radiation transport simulation tool, to determine the secondary gamma rays produced by the primary electrons striking the detector window. We report on the measurement approach and the inferred electron and gamma sensitivities.

9915-86, Session PSun

Further performance evaluation of 2.5 and 5 μm cut-off Hawaii-2RG detectors

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ESO has now delivered or tested in-house, new 5 μm cut-off H2RG detectors, for various projects, such as MATISSE for the VLTI and the upgrade project for CRIRES, the cryogenic high-resolution infrared echelle spectrograph for the VLT. These instruments have required the implementation of some of the more unusual read out options for these detectors, which are may have already been used by other groups, for example, the line-reset-read and line-read-reset modes compared to the standard global reset mode. The detectors are also offered with both output speed options, that is, the standard slow, low noise readout and the faster, higher noise readout, where > 10 frames/s are possible. In the

process of building these detector systems and implementing these new options we have delved deeper into some of the lesser known features of these detectors and tried to characterize them more fully. It is important that these characteristics are well understood before delivery of the next generation of detectors for the ELTs. We obtain very good performance at 2 Mpixel/s speeds with less than 40 e- rms read noise, in all other aspects such as linearity, noise versus number of non-destructive reads and cross talk then their performance of the outputs is the same as slow speed operation. However, the high speed output stages are quite complex to operate, they need to be very well tuned and are prone to oscillation, if not set correctly. We will report on the best bias options to optimize their performance. Likewise we have observed differences between global reset and line reset for the detectors, manifested in a significant increase in detector full well for the line reset option, this also will be reported on. We have also determined that there may signal induced by the detector readout for certain detector material or ROIC revision, at a significant level such that this might be the probable limiting factor of why Fowler sampling reaches a minimum noise value of approximately 3 e- rms for 64 reads and then increases with further non-destructive reads. Finally we also report on some of the other features of the devices where we are still trying to determine if these aspects of performance are a function of the detectors themselves or our controller electronics.

9915-87, Session PSun

A novel reflectometer for relative reflectance measurements of CCDs

Murdock Hart, Robert H. Barkhouser, Stephen A. Smee, Johns Hopkins Univ. (United States); James E. Gunn Sr., Princeton Univ. (United States)

The high quantum efficiencies (QE) of backside illuminated charge coupled devices (CCD) has ushered in the age of the large-scale astronomical survey. The QE of these devices can be greater than 90%, and is dependent upon temperature, the device thickness, backside charging mechanisms, and anti-reflection (AR) coatings. At optical wavelengths the QE can be well approximated as one minus the reflectance, thus the measurement of the backside reflectivity of these devices provides a second independent measure of QE. We have designed and constructed a novel instrument to measure the relative specular reflectance of CCD detectors, with a significant portion of this device being constructed using a 3D fused deposition model (FDM) printer. This device implements both a monitor and measurement photodiode to simultaneously collect input and reflected measurements reducing errors introduced by the relative reflectance calibration process. While most relative reflectometers are highly dependent upon a precisely repeatable target distance for accurate measurements, we have implemented a method of measurement, which virtually eliminates these errors. Using this device we have measured the reflectance of two types of Hamamatsu CCD detectors. The first detector being a 2k x 4k backside illuminated high resistivity silicon detector optimized for use in the 7000 Ang. - 10000 Ang. wavelength range. The second device is similarly a 2k x 4k backside illuminated high resistivity silicon detector, which due to thinning and a different AR coating has been optimized to operate in the 4000 Ang. - 7000 Ang. range. We have not only been able to measure the reflectance of these devices as a function of wavelength, we have also measured the reflectance as a function of position on the device, and found a reflection gradient on these devices.

9915-88, Session PSun

Detector characterization for the Subaru prime focus spectrograph (PFS)

Murdock Hart, Robert H. Barkhouser, Stephen A. Smee, Johns Hopkins Univ. (United States); James E. Gunn Sr., Craig P. Loomis, Princeton Univ. (United States)

The first science grade focal plane array (FPA) for the Subaru Prime Focus Spectrograph (PFS) has been assembled and characterized. PFS will use pairs of Hamamatsu 2k x 4k deep-depletion charge coupled devices (CCDs). We were able to achieve an FPA flatness of less than 2 micron RMS, using a white light confocal microscope for measurement, and selective shims for adjustment. The characterization process for these devices optimized the bias voltages, and measured the quantum efficiency (QE), charge transfer efficiency CTE, gain, and read noise. The reflectance of these devices was also measured as an independent verification of the QE.

9915-89, Session PSun

The ESO 4-Kelvin mid-IR detector test facility

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A crucial requirement for the success of ESO's mid-infrared instruments VISIR and MATISSE is the possibility for extensive laboratory characterization of performance and properties of the 1k x 1k Si:As AQUARIUS detector array. In this context the Thermal Infrared Multi-Mode Instrument TIMMI-2, which was formerly installed at ESO's La Silla 3.6-m telescope, was re-commissioned at ESO headquarters in Germany serving as detector test facility. This instrument provides a 150-liter volume vacuum vessel with integrated cryogenic optics system optimized for the 10-μm and 20-μm-bands, five cryo-mechanisms for apertures, filters, objectives and polarimetric mode selection, a 4-Kelvin cryo-cooler and an IR-window. During the last years it was successively upgraded to a multi-purpose (mid-) infrared detector test facility including external calibration optics for signal chopping, star simulation and drift scan simulation over homogenous background. Emphasis was put on complying with specific electrical, optical, mechanical, thermal and low background requirements of the new detector device. A new AQUARIUS detector mount was developed which allows detector operational temperatures down to 4 Kelvin, whilst at the same time ensuring good shielding characteristics, electrical isolation of the detector system and operating the cryogenic pre-amplifier at 70 Kelvin. We present an overview of the mid-IR test facility capabilities. This will include some latest results on measurements of the test facility optical throughput and the quantum efficiency of the detector device. Another major facility upgrade is planned for 2016 providing significant reduction of thermal background.

9915-91, Session PSun

Second generation large area microchannel plate flat panel phototubes

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Very large (20 cm ? 20 cm) flat panel phototubes are being developed using novel microchannel plates (MCPs). Commercial devices (currently limited to a ~5 cm format) use either conventional MCPs or dynode multipliers for amplification and are readout by a pad array. A program is underway for developing MCPs made by atomic layer deposition (ALD) on a borosilicate microcapillary array which has the potential to advance detector performance beyond that available with conventional MCPs. The borosilicate substrates are robust, including the ability to be produced in large formats (20 cm square) and withstanding high processing temperatures (>700˚C), low intrinsic background (<0.06 events cm-2 sec-1), and high open area ratios (up to 85%). The substrates are functionalized

by the application of resistive and secondary emissive layers using ALD. This allows the operational parameters to be set by tailoring sequential ALD deposition processes. ALD MCPs have performance characteristics (gain, pulse amplitude distributions, and imaging) that are equivalent or better than conventional MCPs. Life testing has shown stable gains during >7 C cm-2 charge extraction after preconditioning (vacuum bake and burn-in). Sealed tube assemblies using a pair of 20 cm ? 20 cm ALD MCPs comprise of a borosilicate entrance window, a proximity focused bialkali photocathode, and a strip-line readout anode. The second generation design employs an all glass body with a hot indium seal and a transfer photocathode. We have achieved >20% quantum efficiency and good gain uniformity over the 400 cm2 field of view, spatial resolution of <1 cm and obtained event timing accuracy of close to 100 ps FWHM.

9915-92, Session PSun

Positional calibrations of the high-purity germanium double-sided strip detectors for the Compton spectrometer and imager

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The Compton Spectrometer and Imager is a medium energy gamma ray (200 keV - 10 MeV) imager designed to observe high-energy processes in the universe from a high altitude balloon platform. At its core, COSI is comprised of twelve high purity germanium double sided strip detectors which measure particle interaction energies and locations with high precision. This manuscript focuses on the positional calibrations of the COSI detectors. The interaction depth in a detector is inferred from the collection time difference (CTD) between the anode and cathode signals. In order to map the CTD measurements back to interaction depths, we modelled the charge transport in the germanium detectors along with the read out electronics and produced simulated anode and cathode signals which yielded the simulated CTD at a given interaction depth. These simulated CTDs were adjusted on a per pixel basis for timing offsets in the read-out electronics and electric field differences across a detector. The X and Y position of an interaction are simply determined by the location of the triggered strips on each side of the detector. However, We investigated the possibility of refining the X and Y positions by using timing information from neighboring "spectator" strips. With the current positional calibrations, COSI achieves an angular resolution of 6.4 degrees FWHM at 662 keV. The theoretical minimum, ignoring detector effects, is approximately 5 degrees at 662 keV. We discuss future work aimed at reducing this margin.

9915-93, Session PSun

Signal dependence of inter-pixel capacitance in hybridized HgCdTe H2RG arrays for use in James Webb Space Telescope's NIRcam

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Inter-pixel capacitance (IPC) is a deterministic electronic coupling by which signal generated in one pixel is measured in a neighboring pixel. Examination of both dark and proton irradiated frames from test NIRcam arrays corroborates earlier results and simulations illustrating a signal dependent coupling. When the signal on an individual pixel is larger, the fractional coupling to nearest neighbors is lesser than when the signal is lower. Frames from test arrays indicate a drop in average coupling from approximately 1.0% at low signals down to approximately 0.7% at high signals.

The photometric ramifications of this non-uniformity are not completely understood. This non-uniformity introduces a non-linearity in the current mathematical model for IPC coupling. IPC coupling has been mathematically formalized as convolution by a blur kernel. Signal dependence requires that the blur kernel be locally defined as a function of signal intensity. Through application of a signal dependent coupling kernel the IPC coupling can be modeled computationally. This method allows for simultaneous knowledge of the intrinsic parameters of the image scene, the impact of a normal imaging system on that scene if IPC were not present, the result of applying a constant IPC, and the result of a signal dependent IPC. Comparison between these results is quantified by changes in SNR, perceived brightness, and centroiding of objects. In the age of sub-pixel precision in astronomy these effects must be properly understood and accounted for in order for the data to accurately represent the object of observation. In addition, this method allows for the validity of corrective filtering techniques to be assessed. The result of using a linear correction on a non-linear data set is explored. By using simulated scenes, which allows access to the intrinsic properties of the scene, the magnitude of error introduced through such techniques is quantified.

Implementation of this method is done through python scripted modeling of image fields including application of established James Webb Space Telescope's NIRcam point spread functions and verified noise simulation and propagation techniques. The introduction of IPC is accomplished through convolution of the image with a blur kernel whose parameters are themselves locally defined functions of the image. These techniques can be used to enhance the data processing pipeline for NIRcam.

9915-94, Session PSun

Design and development of hard x-ray imaging detector using scintillator and SiPhotomultiplier

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Silicon Photomultiplier (SiPM) is a new development in the field of photon detection and can be described as 2D array of small (hundreds of μm2) Avalanche Photodiodes. The Avalanche Photo Diode (APD) operate in Geiger mode, where the output is independent of the number of incoming photons. The gain of each APD is ~ 1e5 - 1e6 electrons. When a photon creates a photoelectron through the photoelectric effect in one of such APD microcells, a large breakdown current is produced. This current through APD is controlled using in-built quenching resistor. The current flow through the parallel combination of APDs is linearly proportional to the number of incoming photons. Hence the SiPM is a linear amplifier device, where the amount of output charge is linearly proportional to the number of incoming photons, as long as these numbers of incoming photons does not exceed the total number of APDs in detection area. SiPM is an alternate option of using conventional PMTs (Photo Multiplier Tubes), as this offers comparable photon detection efficiency, small size, feasibility of compact array, low cost, low operating voltage and insensitivity to the external magnetic field.

Here, we are developing a hard X - ray imaging detector using Scintillator and SiPM devices. In our experiment, we are using CeBr3 Scintillator crystals of size 25 mm x 25 mm x 5 mm, which is optically coupled to SiPM array of size 6 x 6. These SiPMs are sensL make, surface mount device of total size 4 mm x 4 mm with an active area of 3 mm x 3 mm. We are using this setup in two different modes; 1) Total charge output of all SiPMs added together to get the energy information. 2) In the imaging mode to get the X - Y position of the incoming X - ray. We have also carried out this experiment with CsI Scintillator detector of size 15 mm x 15 mm x 3 mm optically coupled with 4 x 4 array of SiPM (SensL make SiPM) for comparison.

We are comparing the photon distribution profile in the Scintillator detector using GEANT4 simulation for different types of Scintillator detectors NaI, CsI, LaBr3, CeBr3, and BGO. This simulation also gives the idea of minimum position accuracy which can be achieved using a particular type of Scintillator.

We will present the preliminary results from the experiment for low energy threshold and the achieved position accuracy and will also provide comparative study of the sizes, thicknesses and type of Scintillator detectors from GEANT4 simulation.

9915-95, Session PSun

A generic FPGA-based detector readout and real-time image processing board

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For space based astronomical observations we don’t have the luxury to use detectors with large readout electronic systems as on ground based telescopes. Moreover the data generated by the image sensor being very large in size cannot be sent completely from the spacecraft to a ground station. Hence a certain amount of real-time image processing is indispensable. An FPGA solution is suitable to develop a generic approach, with respect to various types of detectors, for this task because of the main advantage of easy reconfiguration of the FPGA.

We explored the basic requirements of a generic Real-Time Image processing board. This includes the readout clocks, synchronizing line drivers, RAM requirement for temporary storage and the FPGA implementation of the complete digital logic. We have developed an FPGA board to readout the digital output from the standard semiconductor detectors such as CMOS and CCD. A microcontroller LEON SPARC v8, which is Fault Tolerant to SEU, is implemented on the FPGA to process the images. Various architectures for sharing RAM between the digital logic and the microcontroller were considered.

As an application we have used this board for the readout of a UV CCD. The CCD came with an FPGA board to readout the image data and send in a video format to the computer over USB port. This was replaced by our board which could now readout and process the images in real-time. Image calibrations such as bias, dark and flat field corrections and low level image processing like centroiding and distortion correction is implemented on this board for the UV CCD. The data size reduces from the complete image to a mere list of centroids and their coordinates on the detector.

9915-96, Session PSun

Characterization of an ultraviolet imaging detector with high event rate ROICs (HEROICs) readout

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We present characterization results from a photon counting imaging detector consisting of one microchannel plate (MCP) and an array of two readout integrated circuits (ROIC) that record photon position. The ROICs used in the position readout are the high event rate ROIC (HEROIC) devices designed to handle event rates up to 1 MHz per pixel recently developed by the Ball Aerospace and Technologies Corporation in collaboration with the University of Colorado. An opaque photocathode sensitive in the far-ultraviolet (FUV) is deposited on the upper surface of the MCP. The detector is characterized in a chamber developed by CU Boulder capable of illumination with vacuum-ultraviolet (VUV) monochromatic light and measurement of absolute flux with a calibrated photodiode. Testing includes investigation of the effects of adjustment of internal settings of the HEROIC devices including charge threshold, gain, and amplifier bias. The detector response to high local and global count rates is tested. We report initial results including background, uniformity, resolution, and quantum efficiency (QE) as a function of wavelength.

9915-97, Session PSun

Radiation testing of CID arrays

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A Charge Injection Device (CID) is a broadband (200 to 1100 nm) charge-transfer-device image sensor with a range of innovative capabilities, such as non-destructive readout and random addressability, not normally found in charge-coupled devices (CCDs), CMOS or active pixel sensors. CID imagers with formats up to 4 million pixels are available. Significant improvements in the performance of CID arrays have been achieved in recent years due to the accessibility of smaller feature design rules at commercial silicon foundries. In most imaging devices, radiation normally affects certain key parameters (e.g. gate threshold voltage, field/channel stop threshold voltage, charge transfer efficiency, dark current and noise). The CID technology is inherently “hard” to radiation effects due to the high resistivity of the P-channel process and the individually addressed pixels during readout.

As with any solid-state device, CIDs are susceptible to degraded performance from ionizing and non-ionizing radiation. While CID arrays have been tested for susceptibility to both gamma radiation and neutron fluxes in the past there has been no comprehensive testing of the durability of these devices to proton irradiation. This paper reports on a study conducted at the Lawrence Berkeley National Laboratory 88” Cyclotron using a Thermo Scientific™ CID8825D (18.0 x 16.4 micron pixels, 710 x 484 format) radiation-hardened color camera, which features a new Low-Noise, Preamplifier Per Pixel Radiation Hardened CID imager technology specially designed for use in radiation environments. The resultant CID imager performance tests indicate that the device would perform well in extremely harsh radiation environments.

9915-98, Session PSun

Characterizing persistence in JWST NIRCam flight detectors

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Near-IR detectors are commonly reported to display latent images persisting between integration ramps. After array reset, pixels previously subjected to illumination show an anomalous charge accumulation rate that is initially high but decreases to negligible levels after several hundred

seconds. Depending on the characteristic intensity and timescale, this persistence can dramatically affect science observations if not properly understood. We characterize the persistent behavior of JWST/NIRCam's flight detectors with respect to source intensity, pixel dwell time, and well fill level in order to better understand the underlying physical processes contributing to this phenomenon. Results show that the coefficients of functional fits to the latent signal directly correlate with the stimulating flux as well as the pixel dwell time, enabling predictions of the latent emission. Such relationships provide the potential to model and remove the majority of the persistent flux in NIRCam detectors. Because NIRCam lacks internal calibration lamps, we explore other alternatives to characterize persistence during flight operations.

9915-100, Session PSun

CCD emulator design for LSST camera

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A 3.2G pixel wide-field camera constituting of 189 4K x 4K CCDs is under construction at the LSST project. With each CCD having 16 output channel, a total of 3024 channels are implemented in the camera to enable to read out the full picture in 2 second. As part of the LSST project, a comprehensive CCD emulator corresponding to 3 CCDs have been developed for testing multichannel readout electronics.

Based on an Altera Cyclone V FPGA for timing and control, the emulator generates 48 channels of simulated video waveform in response to appropriate sequence of parallel and serial clocks, which has a speed of 550KSPS. Two 256Mb serial memory is adopted for storage of arbitrary grayscale bitmaps. The bitmap or any test pattern can be generated from the emulator in triple as 3 real CCDs do, verifying and testing the LSST 3-stripe REB(science Raft Electronics Board) simultaneously. Using the method of comparator threshold scanning, all 24 parallel clocks and 24 serial clocks from REB are qualified for sequences, levels and periods, before video signal generation. In addition, 66 channels of input bias and voltages are sampled through multi-channel ADC to verify the correctness of the supply provided to the CCD. In spite of this complexity, a emulator board with medium size and less than 8W power consumption can meet all these requirements.

In addition, either Gigabit Ethernet connector or USB bus can be used for controlling and read back from the emulator board. A user friendly Python software is developed for implementing the automatic REB testing process.

9915-101, Session PSun

Commissioning a MKID for the seeing limited focal plane of the DAG Telescope

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Eastern Anatolia Observatory (DAG) is a 4m class telescope project aimed to build an observatory in Erzurum Turkey to an altitude of 3170m. One of the instruments on the seeing limited Naysmth focus of the telescope starting from 2019 will be a microwave kinetic inductance detector (MKID). DAG-MKID will house and MKID array of 10,000 pixels. Functioning at around 100mK hundred mK temperatures, MKID based instruments allow for the detection of individual photons tagging their wavelength (R-20 at 1 micron) and time of arrival (micro seconds precision) simultaneously. In this poster we provide some information on the technical capabilities of this proposed instrument and the science it will allow.

9915-102, Session PSun

Single event effects in 0.18um CMOS image sensors

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Single Event Effects (SEE) in the on-chip circuitry of CMOS image sensors are discussed. SEE results from heavy ion irradiation are presented. Various design techniques to mitigate against latchup are compared. Latchup and single event upset cross sections are presented at a range of LET up to 109 MeV.cm?/mg.

9915-103, Session PSun

Characterization results of a large format 4k x 4k EMCCD

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Since the advent of the first commercial EMCCD in early 2000, users have been requesting a large format EMCCD that would enable sub-electron read-out noise as well as photon counting. Very high resolution spectroscopy (R>30000) can't be efficiently accomplished on a 1k x 1k device. Wide field surveys looking for transient phenomenon require large format detectors. The 4k x 4k device being developed over the last few years will open-up new possibilities in astronomical instrumentation. Providing the community with rigorous characterization data of this device will allow realistic simulations to be developed to better understand the its potential for foreseen applications.

9915-104, Session PSun

The PizzaBox-1 array controller: a high speed low noise array controller for Teledyne H2RG, H4RG, and Selex SAPHIRA devices

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The PizzaBox-1 (PB-1) array controller provides out of the box functionality for controlling and reading out Teledyne H2RG, H4RG, and Selex SAPHIRA arrays at up to a 3 MHz pixel rate. The PB1 provides 34 readout channels with a single board solution for H2RG and SAPHIRA devices, and provides 68 readout channels with the dual board configuration for supporting the H4RG devices.

The overall operation of the controller is managed through an embedded Linux device integrated into the board design. This embedded device provides a variety of industrial interfaces, such as I2C and SPI, allowing for easy configuration, control, and access to the components that provide much of the functionality designed into the system. The embedded Linux device also provides a set of general purpose I/O (GPIO) lines that are used to interface with the multiple FPGAs used.

Deterministic control and operation of the arrays is accomplished using FPGAs designed for the specific device type being used. FPGAs are also used to move digital pixel data from the ADCs to the data transfer pipe for uploading data to the host PC.

USB 3.0 is used for transferring data to the host PC, and using the integrated USB 3.0 module the PB-1 is capable of providing a 3Mpixel/sec sampling rate per channel, allowing for a 20Hz full frame rate with H2RG devices in high speed mode, and a 1Khz full frame rate with the 320x256 SAPHIRA devices - 4 kHz for a 128x128 sub-array.

The PB-1 accepts an external input trigger for coordinated readouts, and provides two optical outputs, one that can be used for accurate timestamping, and another that allows for controlling and synchronizing other PB-1 controllers for multi-array control.

The embedded Linux device's industry standard serial interfaces allow for on-board sensing of system status. Through functionality integrated into the board accurate real-time telemetry for bias voltages, supply power, array temperatures, and board temperatures, can be collected which provides a high level of insight into system status.

The PB-1 array controller is used for evaluating and characterizing H2RG, H4RG, and SAPHIRA devices, as well as being used to control a H2RG device at high speed in the Daniel K. Inouye Solar Telescope's Cryogenic Near-Infrared Spectro-Polarimeter (CryoNIRSP). Integration into an instrument is straightforward, requiring minimal NRE due to the PB-1's modularity and device specific design. The presentation will provide a review of the measured PB-1 performance, guidelines for evaluating its application for meeting instrument requirements, and outlines a path for integrating the PB-1 into an instrument's overall design.

9915-105, Session PSun

Front-end and slow control electronics for large area SiPMs used for the single mirror Small Size Telescope (SST-1M) of the Cherenkov Telescope Array (CTA)

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A new large area (94 mm2) hexagonal silicon photomultiplier has been developed in collaboration with Hamamatsu for applications in gamma ray astronomy with Imaging Atmospheric Cherenkov Telescopes. A sensor with such a large area poses several challenges in the design of a readout electronics. In this contribution, we review the steps that led to the design of a preamplication stage that allows to reach performances that, scaled by its surface, are comparable to those of conventional SiPMs.

We also describe the slow control electronics that has been designed to stabilize the working point of each of the 1296 sensors employed in the camera prototype of one of the proposed Small Size Telescopes (SSTs) of the Cherenkov Telescope Array (CTA), the single mirror SST (SST-1M). This system exploits the temperature probes implemented within the package of each SiPM to ne-tune the bias voltage (of order 50-60 V) of individual sensors as a function of the instantaneous temperature, with a precision of a few millivolts.

9915-106, Session PSun

Persistence characterization and data calibration scheme for the RSS-NIR H2RG detector on SALT

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To enhance the science capability of the Southern African Large Telescope (SALT), the University of Wisconsin – Madison is building a NIR spectrograph (RSS-NIR). RSS-NIR will complement the visible imaging spectrograph (RSS-VIS) currently available on the telescope. RSS-NIR will deliver medium spectral resolution spectroscopy from 0.9 – 1.7 µm using VPH gratings and a 6 element camera. The detector system uses a H2RG HdCdTe 1.7 µm cutoff array that has been optimized to have low CDS read noise (~20 e-) and fast readout with a pixel sampling speed of 200 kHz. To develop strategies to mitigate persistence, the releasing of trapped charges in subsequent frames, we performed tests to measure and characterize the persistence in the detector. We also performed tests to measure the suppression of the persistence as a function of the relative signal strength between two consecutive frames. These tests use up-the-ramp group samples to get finer time resolution of the release of persistence. The final tests characterizing the persistence of the detector have been completed, and we share these results. We also present preliminary results of the dependence of persistence on detector temperature. We conclude with an outline of a persistence calibration scheme and assess the performance of this routine using the test data.

9915-107, Session PSun

Detector control and data acquisition for the Wide-Field Infrared Survey Telescope (WFIRST) with a custom ASIC

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Modern generation large astronomy focal plane arrays (FPAs) place stringent demands on the control and data acquisition electronic support systems. Most of the detectors used in these FPAs require cryogenic operation, and present interesting signal integrity and thermal isolation trades and challenges. At one extreme, a solution for hybrid detectors is to incorporate ever-increasing function into the Read-Out Integrated Circuit (ROIC). Using modern CMOS designs, these ROICs can be made to include all control and even data acquisition (analog-to-digital conversion, ADC) functions. However, the additional power dissipation at the cold detector may present an undesirable system-level thermal trade. At the other extreme, for small numbers of detectors, it is possible to use only electronics at the warm ambient temperature of the instrument with a relatively simple ROIC. However, this approach requires extreme care in interconnect design since the main thermal break also needs to ensure signal integrity for very small analog signals over potentially large distances.

For NASA's Wide-Field Infrared Survey Telescope (WFIRST) mission, we have a adopted a system-level approach where 1) control and processing intelligence is pushed into components closer to the detector to minimize signal integrity challenges, and 2) functions are performed at the highest allowable temperatures, simplifying the system-level thermal design by not cooling components that do not require such cooling to function. For our design space, the detectors operate at 90K to 100K, the detector control and ADC functions are performed by a custom ASIC at 150K to 180K, and the data processing electronics are at the ambient temperature of the spacecraft, notionally ~300K.

The new ASIC is the main interface between the cryogenic detectors and the warm instrument electronics (an on-board FPGA or computer). This

single-chip design provides basic clocking for most types of hybrid detectors with CMOS ROICs. It includes a flexible but simple to program sequencer, with the option of microprocessor control for more elaborate readout schemes that may be data-dependent. All analog biases, digital clocks, and ADC functions are incorporated and are connected to the nearby detectors with a short cable that also provides some thermal isolation. The interface to the warm electronics is simple and robust through multiple LVDS channels. It also includes design features that support parallel operation of multiple ASICs to control detectors that may have more capability or requirements than can be supported by a single chip.

We report on the design of the new ASIC, current status, and future plans.

9915-108, Session PSun

Design and development of the full scale polar coordinate detector

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The Thirty Meter Telescope project, in collaboration with the Lincoln Laboratory of the Massachusetts Institute of Technology is developing a full scale, 60 x 60 subaperture version of the Polar Coordinate Detector first demonstrated in 2012. The Polar Coordinate Detector is designed to address the problem of adaptive optics (AO) laser guide star (LGS) spot image elongation in Shack Hartmann wavefront sensors for extremely large telescopes. The prototype detector, designated the CCID61, was developed in collaboration with Lincoln Laboratory. The new device is designated the CCID87 and will be used as the LGS wavefront sensor detector in the TMT's first light AO system NFIRAOS. This paper will report on the design and initial test results from the fabrication of the first device lot through front illumination processing.

9915-109, Session PSun

RVS large format arrays for astronomy

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Raytheon Vision Systems (RVS) has a long history of providing state of the art infrared focal planes for the astronomical community. This paper will provide an update of RVS capabilities and products for the community not only for the infrared wavelengths but also in the visible wavelengths as well. Large format infrared detector arrays are now available that meet the demanding requirements of the low background scientific community across the wavelength spectrum. These detector arrays have formats from 1K x 1K to as large as 8K x 8K with pixel sizes ranging from 8 to 27 ?m. Focal plane arrays have been demonstrated with a variety of detector materials: SiPiN, HgCdTe, InSb, and Si:As IBC. All of these detector materials have demonstrated low noise and dark current, high quantum efficiency, and excellent uniformity. All can meet the high performance requirements for low-background within the limits of their respective spectral and operating temperature ranges

9915-110, Session PSun

Prototype near-infrared detectors for WFIRST

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NASA has initiated a technology development effort to produce prototype near-infrared detectors for the WFIRST (Wide Field Infrared Survey Telescope) Project. WFIRST envisions a focal plane array comprised of 18 4K x 4K Sensor Chip Assemblies (SCAs) arranged in a 6 x 3 mosaic. The prototype SCAs have been fabricated by Teledyne Imaging Systems and have a 10um pixel pitch with a 2.5um long wavelength cut-off. Early efforts have focused on variations in the pixel design aimed at optimizing aspects of performance such as image persistence and read noise, which are expected to be key factors in driving the scientific capability of the Wide Field Imaging instrument. We report here on the testing of the prototype detectors at the Goddard Space Flight Center Detector Characterization Lab.

9915-111, Session PSun

Low voltage electron multiplying CCD in a CMOS process

Alice Dunford, Konstantin D. Stefanov, Andrew D. Holland, The Open Univ. (United Kingdom)

Low light level and high speed image sensors as required for space applications can suffer from a decrease in the signal to noise ratio (SNR) due to the photon-starved environment and limitations of the sensor's readout noise. The SNR can be increased by the implementation of Time Delay Integration (TDI) as it allows photoelectrons from multiple exposures to be summed in the charge domain with no added noise. Electron Multiplication (EM) can further improve the signal to noise ratio and lead to an increase in device performance. However, both techniques have traditionally been confined to Charge Coupled Devices (CCD) due to the efficient charge transfer required. With the increase in demand for CMOS sensors with equivalent or superior functionality and performance, this paper presents findings from the analysis of a low voltage EMCCD in a CMOS process using advanced design features to improve gate design and increase the electron multiplying gain. By using CMOS process it is possible to increase chip integration and functionality and achieve higher readout speeds and reduced pixel size. Characterisation tests have been completed including analysis of the dark current, charge transfer efficiency, readout noise, the electron multiplying gain and analysis of the parameters' dependence on temperature and voltage.

9915-112, Session PSun

A temperature controller board for the ARC controller

Simon M. Tulloch, European Southern Observatory (Germany)

A high-performance temperature controller board has been produced for the ARC generation-3 CCD controller. It contains two 9W temperature servo loops and four temperature input channels and is fully programmable via the ARC API and OWL data acquisition program. PI-loop control is implemented in an on-board micro. Both diode and RTD sensors can be used. Control and telemetry data is sent via the ARC backplane although a USB-2 interface is also available. Further functionality includes hardware timers and high current drivers for external shutters and calibration LEDs, an LCD display interface, a parallel i/o port, a pressure sensor interface and an uncommitted analogue telemetry input.

9915-113, Session PSun

Implementation of an FPGA-based DCDS video processor for CCD imaging

Simon M. Tulloch, European Southern Observatory (Germany)

Noise modelling of an E2V CCD231 suggested that a weighted double correlated sampler (DCDS) processor could offer small noise improvements at low pixel rates. The model was used to produce synthetic video waveforms that were then processed at various ADC frequencies and analogue bandwidths to identify the best weighting strategy and preamplifier design. An FPGA-based DCDS controller was then built, first to measure the actual CCD noise spectrum and then to verify the earlier theoretical results.

9915-114, Session PSun

Performance of the Euclid Mission infrared focal plane detector subsystem

Augustyn Waczynski, NASA Goddard Space Flight Ctr. (United States); Rémi Barbier, Institut de Physique Nucléaire de Lyon (France); Steve Cagiano, NASA Goddard Space Flight Ctr. (United States); Jing Chen, Stephanie Cheung, Arctic Slope Regional Corp. (United States); Hyung J. Cho, Jet Propulsion Lab. (United States); Analia Cillis, Univ. of Maryland, Baltimore County (United States); Jean Claude Clémens, Ctr. de Physique des Particules de Marseille (France); Olivia R. Dawson, Jet Propulsion Lab. (United States); Gregory S. Delo, Global Science & Technology, Inc. (United States); Mark Farris, Teledyne Imaging Sensors (United States); Ali R. Feizi, AK Aerospace Technology Corp. (United States); Roger D. Foltz, Mike Hickey, NASA Goddard Space Flight Ctr. (United States); Warren A. Holmes, Jet Propulsion Lab. (United States); Tsuwei Hwang, Arctic Slope Regional Corp. (United States); Ulf E. Israelsson, Jet Propulsion Lab. (United States); Murzy D. Jhabvala, Duncan M. Kahle, Emily Kan, Eric Kan, NASA Goddard Space Flight Ctr. (United States); Markus Loose, Markury Scientific, Inc. (United States); Gennadiy N. Lotkin, Beacon Systems, Inc. (United States); Laddawan R. Miko, Lantrang N. Nguyen, NASA Goddard Space Flight Ctr. (United States); Eric Piquette, Teledyne Imaging Sensors (United States); Timothy J. Powers, Arctic Slope Regional Corp. (United States); Steven H. Pravdo, Allan Runkle, Michael D. Seiffert, Jet Propulsion Lab. (United States); Paolo Strada, European Space Research and Technology Ctr. (Netherlands); Corey Tucker, Arctic Slope Regional Corp. (United States); Kyle Turck, Global Science & Technology, Inc. (United States); Frederick Wang, Arctic Slope Regional Corp. (United States); Carissa T. Weber, Jet Propulsion Lab. (United States); James W. Williams, Global Science & Technology, Inc. (United States)

In support of the European Space Agency's (ESA) Euclid mission, NASA's Detector Characterization Laboratory (DCL) is responsible for the evaluation of the H2RG mercury cadmium telluride (MCT) detectors and electronics assemblies fabricated by Teledyne Imaging Sensors. The detector evaluation is performed in the DCL at the NASA Goddard Space Flight Center (GSFC) in close collaboration with engineers and scientists from the Jet Propulsion Laboratory (JPL) and the Euclid project. The Euclid Near-Infrared Spectrometer and Photometer (NISP) will perform large-area optical and spectroscopic sky surveys in the 0.9 2.02 μm infrared (IR) region. The NISP instrument will contain sixteen 4-megapixel detector arrays each coupled to a Teledyne SIDECAR application specific integrated circuit (ASIC). The focal plane will operate at 100K and the SIDECAR ASIC will be in close proximity operating at a slightly higher temperature of 125K. This paper will describe the test configuration, performance tests, and results of the latest engineering run, also known as Pilot Run. This Pilot Run consisted of four H2RG detectors operating simultaneously. Performance data will be presented on the noise, spectral quantum efficiency, dark current, persistence/latency, pixel yield, pixel-to-pixel uniformity, linearity, inter-pixel crosstalk, full well, dynamic range, power dissipation, thermal response and unit cell input sensitivity.

9915-21, Session 5

Towards the next generation of L-APD MOVPE HgCdTe arrays: beyond the SAPHIRA 320 x 256

Donald N. B. Hall, Univ. of Hawai'i (United States); Ian M. Baker, SELEX ES Ltd. (United Kingdom); Gert Finger, European Southern Observatory (Germany)

The basic Selex SAPHIRA 320 X 256 @24um pitch L-APD MOVPE HgCdTe array is now generally accepted as the sensor of choice for near infrared (NIR – 0.8 to 2.5um) adaptive optics (AO) wavefront(WF) sensing using natural guide stars. With larger formats and improved readout integrated circuits (ROICs), this technology shows great potential for both more sophisticated wavefront correction and also broader, lower background astronomy applications. This opens the path to larger format arrays for optimized for either AO WF sensing or low background applications. We present Selex-UH initiatives in both areas.

The current SAPHIRA arrays are already ideally suited to NIR AO WF tip-tilt sensing using natural guide stars. However applications involving WF sensing for higher order WF correction and correction for aplanatism over the field require larger formats, in the 512 x 512 to 2048 x 2048 range, at maximum pixel read rates. Broader applications involving much lower background astronomical observations require these same larger formats with relaxed requirements on pixel read rate but with reference pixels to track long term drifts. Considerations of cost of the arrays and the instruments utilizing them also drive toward smaller pixels. In the 6 months between submission of abstracts and the SPIE meeting, Selex and UH will replicate planned 320 x 256 @24um pitch developments as 640 x 512 @12um pitch detector arrays and hybridize every alternate row and column of these detector arrays to the ME1001 ROIC to evaluate their performance and develop this technology. Results will be presented as part of this presentation.

For AO WF sensing applications, Selex and UH are pursuing a 1024 x 1024 @12um pitch readout that can be hybridized utilizing every alternate row and column to a 512 x 512 @24um pitch L-APD detector array or to a 1024 x 1024 @12um pitch detector array. The incorporation of 64 outputs with these ROICs will likely require an oversize package – one attractive option is a two-side close-buttable package compatible with the low background 2048 x 2048 @15um pitch, three side close-buttable array summarized below.

UH has already confirmed that the standard MOVPE L-APD design at an avalanche gain of X5 (8 volts avalanche bias) can have gain normalized dark currents as low as 0.01 e-/sec in regions of low glow. This potentially opens the technology to a broad range of lower background astronomical applications. These place a premium on low background and cosmetic quality but are compatible with a lower number of outputs (8, 16 or 32), thus allowing a three-side close-buttable package with all outputs on one side. These applications also require reference outputs and reference pixels

to track and correct long term drifts. Selex and UH are pursuing a 2048 x 2048 @12um pitch, three-side close-buttable array, responsive to these requirements. It would be 2/3 the dimensions of the Teledyne H2RG and mounted on a similar package.

9915-22, Session 5

Next-generation performance of SAPHIRA HgCdTe APDs

Dani E. Atkinson, Donald N. B. Hall, Univ. of Hawai'i (United States); Ian M. Baker, SELEX ES Ltd. (United Kingdom); Sean B. Goebel, Shane M. Jacobson, Univ. of Hawai'i (United States)

We present characterization and deployment performance of the Mark 13/14 and the next generation of Selex SAPHIRA HgCdTe APDs. Iterations on the SAPHIRA hardware, bandgap design, and production methodology have improved the performance and characteristics of the device substantially over the last two years of collaboration between UH and Selex. The Mark 13/14 devices received in Fall 2015 feature a new bandgap design that extends the short-wave response down to 0.8μm. They also marked the introduction of a high-temperature anneal stage during manufacture to bake out surface-level As traps in the HgCdTe. This resulted in a remarkable improvement in cosmetic performance and pixel operability, particularly at high bias voltages where the number of hot/inoperative pixels is greatly suppressed relative to previous SAPHIRA generations. The next generation builds on these successes and specifically targets photon counting.

Our efforts in the reduction of glow generated by the SAPHIRA readout have also greatly reduced measured dark current, and we present new upper limits on dark current in both the Mark 13/14 and next generation SAPHIRA arrays. Using a physical mask we located and identified the primary glow source on the device. The suppression of this source was included in the following round of ROIC redesign. We also present the most recent measurements of other relevant detector characteristics, including avalanche gains of >100 and resulting read noise. Of particular interest for photon counting is the pulse height distribution of avalanche events, for which we also present Monte Carlo modeling of HgCdTe avalanches and discuss agreement with measured data.

9915-23, Session 5

New progress in electron-injection detectors for NIR imagers with low noise and high frame rates

Mohsen Rezaei, Skylar Wheaton, Chee Leong Tan, Vala Fathipour, Melville P. Ulmer, Northwestern Univ. (United States); Olivier Guyon, The Univ. of Arizona (United States); Hooman Mohseni, Northwestern Univ. (United States)

We present our latest simulation and experimental results for a new generation of Electron Injection detectors with a cutoff wavelength of 1.7 um. Electron Injection detectors have an internal linear gain that effectively reduces the noise of the readout electronics. The device is made of the well-developed indium phosphide material system and can be easily made into large imaging arrays with high fill-factor, and it only requires about 1 volt to operate.

Another important property of the device is that it can potentially achieve single-photon detection at about 200 K, and at frame rates of over 1kHz. These properties of a fully developed camera will allow the low-order wavefront sensor in the SCExAO to perform near the photon-noise limit.

We have already fabricated Electron Injection detector arrays with 320x256 pixels at 30 um pitch, and hybridized them with FLIR's ISC9705 readout integrated circuit. We will report the detailed performance of the focal plane array when integrated into a temperature-controlled camera. In particular, we will report the imager overall pixel noise and dynamic range at frame rates up to ~4000 fps, and at different operating temperatures. We also plan to evaluate and report on the performance of the camera in the SCExAO Hilo test facility.

The injector size in these arrays is about 10 um. Our theoretical and experimental results show that smaller injector diameters produce a much lower dark current and higher gain. We plan to make imagers with smaller injector diameter in the future.

This work is supported by a grant from the Keck Foundation.

9915-24, Session 5

RVS WFIRST sensor chip assembly development results

Barry M. Starr, Raytheon Co. (United States)

Raytheon Vision Systems (RVS) has been developing high performance low background VisSWIR focal plane arrays suitable for the NASA WFIRST mission. These near infrared sensor chip assemblies (SCAs) are manufactured using substrate removed HgCdTe on CZT substrates with a 10 micron pixel pitch. WFIRST requirements are for a 4K x 4K format 4-side buttable package to populate a large scale 6 x 3 mosaic focal plane array of 18 SCAs. RVS devices will be compatible with the NASA developed FPA 4-side buttable package, and flight interface electronics. Initial development efforts at RVS have focused on a 2K x 2K format 10 micron pixel design based on an existing readout integrated circuit (ROIC) to demonstrate desired detector material performance at a relevant scale. This paper will provide performance results on the RVS efforts. RVS has successfully developed multiple 4K x 4K 10 micron pixel ROICs and we demonstrate readiness to scale our design efforts to the desired 4K x 4K format for WFIRST in 2016.

9915-25, Session 5

Progress on the characterization activities of new infrared detectors from Selex-ES Ltd. at the UKATC

Naidu N. Bezawada, David C. Atkinson, Chris Miller, Ian Bryson, UK Astronomy Technology Ctr. (United Kingdom); Les G. Hipwood, Nick Shorrocks, Harald J. Weller, Malcolm Jackson, Ray P. Davis, Keith Barnes, Ian M. Baker, SELEX ES Ltd. (United Kingdom)

ESA is funding the industry in Europe to bring the technologies together to manufacture high performance infrared detectors from near infrared (NIR) to very long wavelength infrared (VLWIR) detectors. The UKATC has undertaken the tasks of test and characterising the new detectors being manufactured by Selex ES Ltd in the UK. Initial test results from these programs were presented at previous meetings in 2012 and 2014. The work since has much progressed to test and characterise the Large Format NIR, SWIR and LW and VLWIR detectors. This paper will present the custom built test facilities for evaluation of large format (currently 1280x1032, 15um pixel format) near-infrared detectors for astronomy applications, the characterisation of 1Kx1K shortwave infrared detectors (cut-off at 2.5μm on a 2Kx2K ROIC) for satellite-based earth observation programs, long wavelength (8 to 11μm) and very long wavelength (10 to 14.5μm) 256x320 infrared arrays for cosmos applications. Also being evaluated in our laboratory is a SAPHIRA APD array (mark-5) for photon sensing and high speed AO applications. Custom test facilities have been setup at the UKATC and are being routinely used to test and characterise these detectors under conditions representative of the applications. The paper

will discuss the requirements placed on testing in each of these programs along with the associated challenges to evaluate the performance of these detectors. The paper will also include an overview of Selex detectors and the MOVPE process along with some of the latest test results from the characterisation programs, where appropriate.

9915-27, Session 6

A status report on STA detectors and electronics for 2016

Gregory R. Bredthauer, Kasey L. Boggs, Richard A. Bredthauer, Semiconductor Technology Associates Inc. (United States)

We report on ongoing scientific CCD detector and control electronic developments at STA. Recent astrometric and spectroscopic instruments are pushing for highly uniform pixel arrays. We present results from sensors fabricated with high resolution 1X masks aimed at minimizing the random and periodic pixel nonuniformities introduced during manufacture. Instrument requirements for large next generation telescopes tend to target larger arrays with larger pixels. We introduce the STA4500, a four output 6120 x 6120 15um CCD intended for these applications. The device includes dual transfer gates before the serial register to allow slow, high CTE vertical transfers to occur simultaneous with serial readout. We also present results from our next experimental high dynamic range CCD. This sensor uses dual outputs operating in parallel with different sensitivities to greatly expand the linear dynamic range achievable with large pixel scientific sensors without impairing noise or readout rate. Finally, we describe updates to our Archon astronomical CCD controller. Improvements include daisy chained multi-controller synchronization for mosaic readout, high resolution thermal control for sub-milliKelvin temperature stability, and high voltage biases up to +/-100V for operating deep depletion CCDs.

9915-28, Session 6

Deep depletion CCD detectors for the Transiting Exoplanet Survey Satellite

Vyshnavi Suntharalingam, Ilya Prigozhin, Douglas J. Young, Keith Warner, Barry E. Burke, Joseph S. Ciampi, Michael J. Cooper, Renee D. Lambert, Daniel M. O'Mara, Deborah F. Woods, MIT Lincoln Lab. (United States); Steven E. Kissel, Kavli Institute for Astrophysics and Space Research (United States); Gregory Y. Prigozhin, Timothy A. Sauerwein, Carolyn Thayer, Joel S. Villasenor, MIT Kavli Institute for Astrophysics and Space Research (United States)

We describe the development of the fully depleted, back-illuminated, charge coupled devices for the Transiting Exoplanet Survey Satellite (TESS). The TESS payload consists of four identical wide-angle cameras, each having a 2x2 mosaic array of CCDs in its focal plane. The devices are fabricated from start to finish on the newly upgraded 200-mm wafer line at Lincoln Laboratory. The specifications for TESS required thick (100μm) fully depleted CCDs with 2048x2048 imaging array and 2048x2048 frame store regions, 15x15μm pixels, and 4 output ports. Rapid (~4msec) frame transfer and high (>200,000 electrons) well capacity are required, as well as charge injection and binning.

We discuss techniques used to produce the devices on high resistivity substrates, including techniques to stitch, or photocompose, the 32mm x 64mm die with stepper lithography. We describe the packaging methods for 3-side abuttable arrays with 10-micron peak-to-valley flatness. Finally, we present both wafer-level and packaged device performance results, with specific discussion of the accomplishments with low dark current (<2e-/pix/sec at -30°C wafer probe), high QE (>60% at 950nm), low noise (<10e- at 625kHz), high full well (>200ke), and detector-bias controlled PSF.

9915-29, Session 6

Technology validation of the PLATO CCD at ESA

Thibaut Prod'homme, Peter Verhoeve, Thierry Beaufort, Ludovic Duvet, Frederic Lemmel, Hans Smit, Sander Blommaert, Cornelis van der Luijt, European Space Research and Technology Ctr. (Netherlands); Ivo Visser, Klok Vacuum Service (Netherlands); Jerko Heijnen, Bart Butler, European Space Research and Technology Ctr. (Netherlands)

PLATO – PLAnetary Transits and Oscillations of stars – is the third medium-class mission (M3) to be selected in the European Space Agency (ESA) Science and Robotic Exploration Cosmic Vision programme. It is due for launch in 2024 with the main objective to find and study terrestrial planets in the habitable zone around solar-like stars. The payload consists in 34 cameras; with each camera comprising 4 Charge-Coupled Devices (CCDs), a total of 136 flight model devices procured by ESA shall ultimately be integrated on the spacecraft. The CCD270 – specially designed and manufactured by e2v for the PLATO mission – is a large format (8 cm x 8 cm) back-illuminated device operating at 4 MHz pixel rate and coming in two variants: full frame and frame transfer. Due to the large number of devices and its demanding specifications, the manufacturing of the PLATO CCDs is an unprecedented industrial effort in many aspects.

In order to de-risk the PLATO CCD procurement and aid the mission definition process, ESA's Payload Technology Validation team is currently validating the PLATO CCD270. This validation consists in demonstrating that the device achieves its specified electro-optical performance in the relevant environment: operated at 4 MHz, at cold and before and after proton irradiation. It also includes investigating if the CCD280 – a smaller device produced on the same wafer as the CCD270 – can be used instead of the CCD270 for radiation testing during qualification.

In the context of this validation, two CCD270 and two CCD280 devices have been fully characterized before and after proton irradiation. This paper details the test results with respect to dark current, hot pixels, random telegraph signals and charge transfer inefficiency. It shall focus in particular on the latter, discussing our findings related to the use of a variety of measurement methods (x-ray, flat-field extended pixel edge response, first pixel response, trap pumping) characterizing radiation-induced, charge trapping defects at high readout frequency – a rather unexplored region for Astronomy applications. The outcome of this test campaign shall serve as a direct input to the PLATO consortium of scientists to study the mission end-of-life performance and as a basis for further optimization of the CCD operation.

9915-30, Session 6

Characterization and acceptance testing of fully depleted thick CCDs for the Large Synoptic Survey Telescope

Ivan V. Kotov, Paul O'Connor, Justine Haupt, Brookhaven National Lab. (United States); Homer Niel, SLAC National Accelerator Lab. (United States)

The LSST came will be made as a mosaic assembled of 189 large format Charge Coupled Devises (CCD). These are n-channel, 100 micron thick devices operated in over depleted regime. There are 16 segments, 1 million

pixels each, read out through separate amplifiers. The image quality and readout speed expected from LSST camera translates into strict acceptance requirements for individual sensors.

Prototype sensors and preproduction CCDs were delivered by vendors and been used for developing test procedures and protocols. Building upon this experience 2 test stands were designed and commissioned at Brookhaven National Laboratory for production electro-optical testing.

Sensor acceptance criteria are outlined and discussed. The test stand design and equipment used in its design is present. The results of commissioning sensor runs are present.

9915-31, Session 7

Performance of ?c=2.5µm HAWAII 4RG-15 (H4RG-15) arrays in the laboratory and at the telescope

Donald N. B. Hall, Dani E. Atkinson, Univ. of Hawai'i (United States); Richard Blank, AstroBlank Scientific LLC (United States); Mark Farris, Teledyne Imaging Sensors (United States); Sean B. Goebel, Klaus W. Hodapp, Shane M. Jacobson, Univ. of Hawai'i (United States); Markus Loose, Markury Scientific, Inc. (United States); Majid Zandian, Teledyne Imaging Sensors (United States)

The NSF supported development of the HAWAII 4RG-15 (H4RG-15) aims to provide a 16 MPxl 4096x4096@15?m pitch format array at significantly reduced price per pixel while maintaining the superb low background performance of the H2RG. The design also incorporates new features, notably clocked reference output and interleaved reference pixel readout, that promise to significantly improve noise performance; the reduction in pixel pitch from 18 to 15 microns may slightly improve transimpedance gain with modest potential impact on full well and crosstalk.

The program is segmented into 1) technology development and, 2) production demonstration phases. Phase 1, completed in June of 2012, developed and demonstrated all key technologies in four engineering grade H4RG-15 arrays. The measured performance of these arrays resulted in the selection of the ON Semiconductor ROIC for Phase 2. Initiation of the Phase 2 program to attempt six hybridizations with a goal of two science grade H4RG-15 arrays was delayed due to challenges in growing high quality MBE layers on the 7 x 7.5cm substrates required for the H4RG-15. These were surmounted in July of 2015 and, at the time this abstract is being submitted, seven excellent MBE layers are in the final stages of detector processing with hybridization scheduled early in 2016. These H4RG-15 arrays will be available to UH in March, 2016 for characterization both in the laboratory and at the UH 88-inch telescope on Mauna Kea.

We will report the performance of these Phase-2 H4RG-15s within the context of established H2RG performance for key parameters (read noise, dark current, transimpedance gain, and cross-talk), highlighting the improvements from the new readout modes.

9915-32, Session 7

Integrated system tests of the LSST raft tower modules

Paul O'Connor, Brookhaven National Lab. (United States); Pierre E. Antilogus, Institut National de Physique Nucléaire et de Physique des Particules (France); Peter E. Doherty, Harvard Univ. (United States); Justine Haupt, Brookhaven National Lab. (United States); Sven C. Herrmann, Michael Huffer, SLAC National Accelerator Lab. (United States); Claire Juramy, Institut National de Physique Nucléaire et de Physique des Particules (France); John Kuczewski, Brookhaven National Lab. (United States); Stefano Russo, Institut National de Physique Nucléaire et de Physique des Particules (France); Christopher W. Stubbs, Harvard Univ. (United States); Richard Van Berg, Univ. of Pennsylvania (United States)

The science focal plane of the LSST camera is made up of 21 fully autonomous 144 Mpixel imager units designated "raft tower modules" (RTM). These imagers incorporate nine 4K x 4K fully-depleted CCDs and 48 channels of readout electronics, including a dedicated CMOS video processing ASIC and components that provide CCD biasing and clocking, video digitization, thermal stabilization, and a high degree of monitoring and telemetry. The RTM achieves its performance goals for readout speed, read noise, linearity, and crosstalk with a power budget of less than 400mW/channel. Series production is underway on the first units and will run until 2018.

We will present the RTM final design, tests of the integrated signal chain, and performance results for the fully-integrated module with pre-production CCDs.

9915-33, Session 7

Development of low-noise CCD drive electronics for the World Space Observatory ultra-violet spectrograph subsystem

Mike A. Salter, Matthew J. Clapp, Nick R. Waltham, Science and Technology Facilities Council (United Kingdom)

World Space Observatory Ultra-Violet (WSO-UV) is a major Russian-led international collaboration to develop a large space-borne 1.7 m Ritchey-Chrétien telescope and instrumentation to study the universe at ultra-violet wavelengths between 115 nm and 310 nm, exceeding the current capabilities of ground-based instruments. The WSO Ultra-Violet Spectrograph subsystem (WUVS) is led by the Institute of Astronomy of the Russian Academy of Sciences and consists of two high resolution spectrographs covering the Far-UV range of 115-176 nm and the Near-UV range of 174-310 nm, and a long-slit spectrograph covering the wavelength range of 115-305 nm. The custom-designed CCD sensors and cryostat assemblies are being provided by e2v technologies (UK). STFC RAL Space is providing the Camera Electronics Boxes (CEBs) which house the CCD drive electronics for each of the three WUVS channels.

This paper presents the results of the detailed characterisation of the WUVS CCD drive electronics. The electronics include a novel high-performance video channel design that utilises Digital Correlated Double Sampling (DCDS) to enable low-noise readout of the CCD at a range of pixel frequencies, including a baseline requirement of less than 3 electrons rms readout noise for the combined CCD and electronics system at a readout rate of 50 kpixels/s. These results illustrate the performance of this new video architecture as part of a wider electronics sub-system that is designed for use in the space environment. In addition to the DCDS video channels, the CEB provides all the bias voltages and clocking waveforms required to operate the CCD and the system is fully programmable via a primary and redundant SpaceWire interface. The development of the CEB electronics design has undergone critical design review and the results presented were obtained using the engineering-level electronics box. A variety of parameters and tests are included ranging from general system metrics, such as the power and mass, to more detailed analysis of the video performance including noise, linearity, crosstalk, gain stability and transient response.

9915-34, Session 7

Optical characterization of the PLATO CCD at ESA

Peter Verhoeve, Thibaut Prod'homme, Tim Oosterbroek, Ludovic Duvet, Thierry Beaufort, Sander Blommaert, Bart Butler, Jerko Heijnen, Frederic Lemmel, Cornelis van der Luijt, Hans Smit, Ivo Visser, European Space Research and Technology Ctr. (Netherlands)

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In order to de-risk the PLATO CCD procurement and aid the mission definition process, ESA's Payload Technology Validation section is currently validating the PLATO CCD270. This validation consists in demonstrating that the device achieves its specified electro-optical performance in the relevant environment: operated at 4 MHz, at cold and before and after proton irradiation.

In the context of this validation, CCD270 devices have been characterized optically with respect to performance parameters directly relevant for the photometric application of the CCDs. This paper details the results of measurements of Quantum Efficiency for a range of angles of incidence, Pixel Response Non Uniformity, intra–pixel response (non-)uniformity, and response to spot illumination, before and after proton irradiation. In particular, the effect of radiation induced degradation of the charge transfer efficiency on the measured charge in a star-like spot has been studied as a function of signal level and of position on the pixel grid. Also, the effect of various levels of background light on the amount of charge lost from a star image will be described. The outcome of this test campaign shall serve as a direct input to the PLATO consortium of scientists to study the mission performance and as a basis for further optimization of the CCD operation.

9915-35, Session 7

On-ground characterization of the Euclid's CCD273-based readout chain

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Euclid is a medium class European Space Agency mission scheduled for launch in 2020. The main goal of the survey is to study the dark matter and energy content of the Universe. One of the cosmological probes used, the Weak Lensing technique, looks at distortions in galaxy shapes and requires very accurate knowledge of the system point spread function (PSF). To measure those shapes with maximum accuracy the camera system of the telescope's VISible Instrument (VIS) needs to provide high charge transfer efficiency and low noise operation. A single readout chain of VIS consists of 3 CCDs, readout electronics (ROE) and a power supply unit (RPSU). The entire Euclid focal plane for flight features 36 CCDs, which are read out by 12 ROEs and powered by 12 RPSUs. All three components of the readout chain have been explicitly designed for Euclid. The CCD273 device manufactured by e2v provides maximum charge transfer efficiency to reduce the charge trailing during the readout. The CCD is also fitted with a charge injection structure which is used for the calibration of the Charge Transfer Inefficiency. The readout electronics (ROE) and the ROE power supply unit (RPSU) have been designed and manufactured at the Mullard Space Science Laboratory (MSSL) and offer low noise, radiation-resistant operation.

The VIS readout chain undergoes a rigorous on-ground testing at several development stages to guarantee that strict mission requirements are met before the launch of the telescope. This paper summarizes the results of the commissioning of an advanced flight-like VIS readout chain consisting of an electro-mechanical model (EM) of the CCD273 device, EM ROE and EM RPSU. In particular, the chosen CCD operation modes, design trade-offs and performance parameters are discussed. Aspects to improve uniformity and stability of device operation are addressed as well.

9915-36, Session 8

LGSD/NGSD: high QE, 3e-RoN, fast 700fps, 1760x1680 pixels, AO LGS CMOS imager for the E-ELT

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The success of the next generation of instruments for ELT class telescopes will depend upon improving the image quality by exploiting sophisticated Adaptive Optics (AO) systems. One of the critical components of the AO systems for the E-ELT has been identified as the optical Laser/Natural Guide Star WFS detector. The combination of large format, 1760x1680 of 24 ?m pixels to finely sample the wavefront and the spot elongation of laser guide stars, fast frame rate of 700 frames per second (fps), low read noise (< 3e-), and high QE (>90%) makes the development of this device extremely challenging. Design studies concluded that a highly integrated Backside Illuminated CMOS Imager built on High Resistivity silicon as the most likely technology to succeed.

Two generations of the CMOS Imager are being developed: a) the already designed and manufactured NGSD, a quarter sized pioneering device of 880x840 pixels capable of meeting first light needs of the E-ELT; b) the LGSD, the larger full size device. The detailed design is presented including the approach of using massive parallelism (70,400 ADCs) to achieve the low read noise at high pixel rates of 3 Gpixel/s and the 88 channel, 220 Mbps, LVDS serial interface to get the digitized data off-chip. To enable read noise closer to the goal of 1e- to be achieved, a split wafer run has allowed the NGSD to be manufactured in the more speculative, but much lower read noise, Ultra Low Threshold Transistors in the unit cell. The NGSD has come out of production, it has been thinned to 12?m, backside processed and packaged in a custom 370pin Ceramic PGA (Pin Grid Array).

Results of comprehensive tests performed both at e2v and ESO have validated the technological choice. These results along with the plan for a further tweaking of the design to solve the remaining issues of hot pixels and cross-talk are presented.

9915-38, Session 8

Fully depleted backside biased CMOS image sensor

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We are presenting a novel concept for a fully depleted, pinned photodiode CMOS image sensor using reverse substrate bias. The principle of operation allows the manufacture of fully depleted, backside illuminated CMOS sensors with active thickness in excess of 100 μm. This helps increase the QE at near-IR and soft X-ray wavelengths, while preserving the excellent characteristics associated with the pinned photodiode sensitive elements. Such sensors are applicable to wide range of applications, including scientific imaging, astronomy, Earth observation and surveillance.

A prototype device with 10 μm and 5.4 μm pixels using this concept has been designed and manufactured on a 0.18 μm image sensor process. An additional implantation step has been introduced in order to achieve full depletion without large parasitic substrate currents. The paper discusses the design of the sensor and the challenges that had to be overcome to realise it in practice. The first characterisation data from a number of design variants is presented and discussed, as well as the plans for producing full scale devices in the near future. It is expected that this new technology can be competitive with modern backside illuminated thick CCD for use at visible to near-IR telescopes and synchrotron light sources.

9915-39, Session 8

A 9 megapixel large-area back-thinned CMOS sensor with high sensitivity and high frame-rate for the TAOS II program

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The Transneptunian Automated Occultation Survey (TAOS II) is a robotic telescope system using three telescopes in San Pedro Martir Observatory in Mexico. It measures occultation of background stars by small TransNeptunian Objects in order to determine their size distribution. Each telescope focal plane uses ten buttable backthinned CMOS sensors. Key performance features of the sensors are: Large array format 4608 x 1920, Pixel size 16μm, Multi ROIs, 8 analogue video channels, Frame rate of 20-40 fps [using ROIs], Low noise <5e-, Cryogenic dark current <0.1e-/pixel/s, backthinned for >90% peak quantum efficiency.

The paper describes top level application requirements for the TAOS II detector. The sensor design including the pixel and buttable package are described together with performance at room temperature and cryogenic temperature of backthinned devices. The key performance specifications have been demonstrated and will be presented. The production set of 40 devices are due for completion within 2016.

9915-40, Session 8

Electro-optic and radiation damage performance of the CIS115: an imaging sensor for the JANUS optical camera on-board JUICE

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The Jupiter Icy Moon Explorer (JUICE) has been officially adopted as the next Large-class mission by the European Space Agency, with a launch date of 2022. The science payload includes an optical camera, JANUS, which will perform imaging and mapping observations of Jupiter, its moons and icy rings across a 1.72 ? 1.29 degree^2 field of view. A 13 slot filter wheel will be used to provide spectral information in order for the JANUS experiment to study the geology and physical properties of Ganymede, Europa and Io, and to investigate processes and structures in the atmosphere of Jupiter.

The sensor selected for JANUS is the back-thinned CIS115, a 3 MPixel CMOS Image Sensor from e2v technologies. The CIS115 has a 4-Transistor pixel design with a pinned photodiode to improve signal to noise performance by reducing dark current and allow for reset level subtraction. The JUICE mission will consist of an 8 year cruise phase followed by a 3 year science phase in the Jovian system. Models of the radiation environment throughout the JUICE mission predict that the End of Life (EOL) non-ionising damage will be equivalent to 10^10 10 MeV protons and the EOL ionising dose will be 100 krad(Si), once the shielding from the spacecraft and instrument design is taken into account. An extensive radiation campaign is therefore being carried to qualify and characterise the CIS115 for JANUS, as well as other space and terrestrial applications.

Radiation testing to take the CIS115 to twice the ionising dose and displacement damage levels was completed in 2015. Good sensor performance was observed following irradiation and a summary of the key results will be presented here, including changes to the readout noise, image lag, the dark current between -55˚C and 40˚C, and the observed flat-band voltage shift. In 2016, further radiation campaigns on flight-representative CIS115s will be undertaken and will include an electron irradiation campaign since electrons are the primary damaging particle expected in the Jovian environment. Latest results will be presented and comparisons to earlier gamma and proton campaigns will be drawn.

9915-41, Session 9

An overview of advanced development and field observations with delta-doped arrays in ground-based observatories, suborbital missions, and satellite missions

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A number of exciting concepts are under development for flagship, Explorer, and suborbital missions in the ultraviolet/optical spectral range, including various concepts for a Next Generation large aperture UV/optical telescope. These missions will depend on high performance silicon detector arrays to be delivered affordably and in high numbers. In a focused effort, and through investments by NASA, industry, and JPL-

internal funds, we have advanced delta-doping technology from small-scale processing to high throughput and high yield scale, and we have demonstrated delta-doping technology with a multitude of CCD and CMOS detector formats and designs. We have embarked on a number of field observations, instrument integration, and independent evaluation of delta-doped arrays as part of this technology advancement and in preparation for upcoming missions,

Delta-doped arrays have been independently evaluated and have had their performance verified by various groups, including the group led by the Kepler PI for precision photometry. Delta-doped CCDs of various formats have successfully flown on multiple suborbital flights, including several sounding rockets with the University of Colorado, Johns Hopkins University, and Cornell/ Dartmouth/ Southwest Research Institute (SwRI). A delta-doped and atomic layer deposition (ALD) antireflection (AR)-coated electron-multiplying CCD (EMCCD -- e2v CCD201) is being delivered to Caltech for Faint Intergalactic Redshifted Emission Balloon (FIREBall), a stratospheric balloon payload. A 12-megapixel fully-depleted p-channel delta doped array designed at Lawrence Berkeley National Laboratory (LBNL), fabricated at DALSA, and post-fab processed at JPL will also fly on University of Colorado's CHESS (Colorado High-resolution Echelle Stellar Spectrograph) rocket. Recent and ongoing ground-based observations include a delta-doped, AR-coated EMCCD at Palomar's Cosmic Web Imager (CWI) and the delta doped p-channel arrays (bare and coated) at Mount Bigelow.

In this paper, we present recent developments of JPL's Advanced Detectors and Systems program, including delta-doping technology; JPL's end-to-end post fabrication of high performance delta-doped arrays; advanced coatings (for detectors and optical elements), and various instrument integrations. We present examples of past, in-progress, and planned observations and deployments of delta-doped arrays.

9915-42, Session 9

High accuracy measurements of the intrapixel sensitivity of VIS to LWIR astronomical detectors: experimental demonstration

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The reduction of systematic effects is necessary to improve the level of accuracy in imaging and astrometry. For example, in Euclid Mission which aims at carrying out accurate measurements of dark energy and quantifying precisely its role in the evolution of the Universe, the systematic effects need to be controlled to a level better than 10-7 (Euclid, Science Book). To achieve this goal, a high-level of knowledge of the system point spread function (PSF) is required. The system PSF is a combination of the performance of the optical system, space-craft pointing accuracy, pixellisation and intrapixel sensitivity. The intrapixel sensitivity, often neglected, represents in the case of under-sampled instruments a non-negligible contribution in the error budget. For this reason, the measurement of the detector intrapixel sensitivity is already required by ESA in detector technology development activities.

This paper follows the concept-paper presented at the last SPIE conference and gives the recent developments achieved in the design of the test bench for the intrapixel sensitivity measurements. The measurement technique we use is based on the projection of a high spatial resolution periodic pattern on the detector using the self-imaging property of a new class of diffractive objects named continuously self-imaging gratings (CSIG) and developed at ONERA. The principle combines the potential of global techniques, which make measurements at once on the whole FPA, and the accuracy of spot-scan-based techniques, for which high local precisions can be achieved. To reconstruct a pixel profile with a resolution of a 10th of a pixel, it is necessary to explore MTF up to high spatial frequencies, 10 times higher than the pixel Nyquist frequency. To avoid aliasing effect, the procedure consists in performing a microscan of the self-image produced by the CSIG in front of the tested detector at a step of pixel pitch/10. An appropriate deconvolution algorithm is then used to reconstruct the pixel profile at a local scale (one pixel) or a semi-global scale (NxN pixels). This algorithm has been tested and validated on simulated images.

A demonstrator test bench working in the visible spectral range has been designed and commissioned to experimentally validate the microscan-based local technique. A CSIG corresponding to the extended spatial frequency range to explore has been designed and mounted on a 2D axis translation stage in order to perform the microscan. The under-sampled images acquired are recombined in order to obtain an over-sampled interferogram corresponding to the self-image of the CSIG. This recombination is performed by an interpolation-based algorithm. The deconvolution algorithm then allows to reconstruct the estimated pixel profile. This visible demonstrator prepares the future version of a unique test bench working from visible to LWIR (7 μm to 11 μm) spectral ranges.

The paper will detail the latest improvements. It will also discuss the well-appropriated architecture solutions for the final test bench. Considering the visible demonstrator as an intermediate step, we will address how to overcome the limitations encountered in the demonstrator to design the final test bench.

9915-43, Session 9

Ultraviolet/optical detector coatings for ground-based, suborbital, and satellite astronomy and astrophysics

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Here we describe the development of optical coatings for silicon-based detectors for astronomy and astrophysics. JPL's delta- and superlattice-doped (2D-doped) silicon arrays exhibit 100% internal quantum efficiency (QE) spanning the UV and visible wavelength ranges. This reflection-limited response can be further improved with optical coatings. At JPL, thin-film filters and antireflection coatings are incorporated with existing detector technologies by atomic layer deposition (ALD). Using ALD we are able to achieve precision growth of nanometer-scale multilayer optical films to provide tailored, repeatable performance for targeted band passes on a variety of detector platforms, including CCD, EMCCD, CMOS, and APD. Recent examples include broadband detectors with >70% QE spanning 300-900 nm, offering unprecedented sensitivity for ground-based observations, as well as a 2D-doped detector with absolute QE >70% at 205 nm for the Faint Intergalactic Red-shifted Emission Balloon (FIREBall-2) experiment. We will review coating development and detector performance for these applications, as well as review possibilities for future satellite missions. We will also briefly describe the development of solar-blind silicon detectors with high UV performance and >103 out-of-band rejection (i.e., red rejection); this topic will be covered in greater detail in complementary paper presented at this conference.

9915-44, Session 9

Solar-blind superlattice-doped avalanche photodiodes

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Large area solid state detectors with sensitivity around 200 nm and nanosecond rise times have potential applications in astrophysics and high energy physics. Next generation high energy physics experiments require detectors of high energy gamma rays that can withstand unprecedented rates and radiation doses. Current experiments employ crystals such as PbWO4 or LYSO, which have scintillation decay times of ~30ns, which is too slow for the new high rate experiments being studied for the 2020s and beyond. There is a faster crystal, BaF2, with a scintillation component having a 0.9 ns decay time at 220nm that would be a good match to this task. The fast component is, however, accompanied by a larger (85% of the light) slow component (650 ns at 330nm).

We report the development of gamma ray scintillator technology with subnanosecond temporal resolution and the capability to withstand unprecedented rates and doses of high energy gamma radiation. The system consists of doped BaF2 scintillating crystals and solar-blind silicon avalanche photodiodes for detecting the fast scintillation component of BaF2. High efficiency and fast response are achieved by using molecular beam epitaxy to grow a doping superlattice on the avalanche photodiode. Integrated solar-blind antireflective coatings formed by atomic layer deposition enable efficient detection of the fast BaF2 scintillation at 220nm, with strong suppression of the slow BaF2 scintillation at 330nm.

The ultrafast response time of these detectors is ideal for NASA applications such as X-ray pulsar navigation, time-gated Raman spectroscopy, and planetary gamma ray spectrometers. NASA has flown a number of instruments and missions using scintillation detectors, including MESSENGER's Gamma ray and neutron spectrometer; the CGRO Energetic Gamma Ray Experiment Telescope (CGRO/EGRET); the Fermi Large Area Telescope (Fermi/LAT); and the Fermi Gamma-Ray Burst Monitor (Fermi/GBM). The unique capabilities of this subnanosecond scintillation detector are an enabling technology for NASA's Advanced Compton Telescope and other missions requiring high efficiency gamma-ray detection with excellent time resolution, such as a follow-on to the Fermi-LAT.

9915-45, Session 9

Generic integration-time hysteretic sensor response revealed in CCD photon transfer statistics and implications for high fidelity point-spread function retrieval: connecting recorded signal to incident flux distribution in high dynamic range exposures

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We conjoin electrostatic conversion drift calculations to CCD pixel signal covariances observed in flat field exposures. We thus constrain pixel geometry distortions present at exposure end, based on signal images recorded. We use available data from several operational astronomical sensor technologies to validate our understanding. Our primary goal is to optimize flux point spread function (FPSF) estimation quantitatively, and thereby minimize sensor-induced errors which may limit precision astronomy performance. We consider alternative compensation scenarios that will take maximum advantage of our understanding of this underlying mechanism, in data processing pipelines currently under development.

9915-46, Session 10

Properties of DePFET active pixel sensors fabricated in an industrial CMOS foundry

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Modern state-of-the-art CMOS processes offer a wide spectrum of advantages compared to research laboratory style fabrications, provided that the physical key parameters needed for a good detector performance are preserved: low leakage currents, defect free double sided handling, and a good Si-SiO2 interface quality to mention some of the relevant parameters. We developed a fabrication process in an industrial CMOS foundry which fulfills the above boundary conditions and facilitates the production of backside-illuminated DEPFET active pixel sensors on 725 μm thick, double sided polished high resistivity float-zone silicon. The foundry offers further, high process stability, smaller feature sizes, more complex additional circuitry and a higher throughput in a shorter time. Based on a technology test fabrication which yielded promising results, we have started such a detector fabrication. The first DEPFET devices ever built in an industrial-scale CMOS fab will be available early next year and their properties will be presented together with the outcome of already existing test devices. Given the customized CMOS process we have simulated the final device properties in two and three dimensions to extract the sensor relevant electrical properties, such as (a) transconductance, (b) internal gate depth, (c) clear functionality, (d) clear speed, (e) analog storage of signal charge and (f) internal gate capacitance. All those parameters are required to safely predict the performance figures of the DEPFET sensor. Based on our simulation experience, which led to a very good agreement between simulations and measurements for recent DEPFET fabrications, we derived the properties for a 50 x 50 μm? pixel design. These pixels can be realized with an amplification of more than 1.5 nA/electron with a charge handling capacity of 100.000 signal charges. Due to the CMOS process which allows for smaller DEPFET dimensions these devices can be completely cleared with moderate voltages within 100 ns. Beginning of next year these characteristics will be verified on real devices and their overall capabilities for X-ray imaging and spectroscopy will be summarized. In addition, a concept of a large, high resolution X-ray imager and its deduced characteristics will be presented. The already proven DEPFET features will be highlighted in view of the new options of the industrial fabrication process: repetitive non-destructive readout, gating, high charge handling capacity through non-linear amplification and analog signal storage.

9915-48, Session 10

Spectral performances of Kyoto's x-ray astronomical SOI pixel sensor in the frame and event-driven readout modes

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We have been developing monolithic active pixel sensors, X-ray SOIPIXs based on a Silicon-On-Insulator (SOI) CMOS technology for future X-ray astronomy satellites (eg. Tsuru et al. SPIE AS14, arXiv:1408.4556). Immediate readout of only the pixels hit by X-rays is available by an event trigger output function implemented in each pixel with its high time resolution of better than 10 usec (event-driven readout). It allows us to do fast timing observation and also reduce non-X-ray background dominating at high X-ray energy band above 5-10 keV by adopting an anti-coincidence technique.

We propose the X-ray SOIPIXs as a soft X-ray sensors of wide-band hybrid X-ray imagers of a next Japanese mission, FORCE (FOcusing Relativistic universe and Cosmic Evolution), which is characterized by broadband (1-80 keV) X-ray imaging spectroscopy with high angular resolution (<15"), reaching to about 10 times the sensitivity compared to previous missions above 10 keV (See Mori et al. in AS102).

In this presentation, we report followings subjects.

(1) Reduction of interference in the event-drive readout mode. As reported in AS14, we have already reached the readout noise of ~32e (rms) in the frame readout mode, in which all the pixels data are read out serially like CCD. However, the spectral performance is still poor in the event-driven readout mode. The readout noise is ~150e (rms) and an offset is observed in the correlation between the pulse-height and X-ray energy. They are caused by interference due to a capacitive coupling between a comparator in the circuit layer and a charge collecting node in the sensor layer of the high resistivity silicon. Thus, we newly developed X-ray SOIPIXs using a double SOI wafer having a low resistivity silicon layer between the circuit and sensor layers.

The device successfully reduces the interference and the offset.

(2) Sensitivity in the low energy X-ray band. Since the circuit layer has the thickness of ~8um, a backside illumination (BI) is essential to observed low energy X-rays. Thus, we developed BI types of X-ray SOIPIXs by using the process of ion implantation and laser annealing. X-ray measurements revealed the the thickness of the dead layer of ~2um. In order to do further reduction, we fabricated devices whose backsides were processed by the "Pizza" process developed by LBNL, in which the ion implantation is followed by a low temperature annealing. The Pizza process successfully reduced the dead layer to ~1um, which fulfills the requirements of the FORCE mission. We are now trying another process aiming at a further reduction.

(3) Large sized device. We completed in Dec. 2015 the production of 3-side buttable devices with a pixel size of 36um and the imaging area of 22mm x 14mm. It also has a new peripheral readout circuits (PGA and differential readout). We report results from initial tests of the device in the presentation.

9915-50, Session 10

The HEXITEC hard x-ray pixelated CdTe imager for fast solar observations

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The HEXITEC CdTe Imager (for High Energy X-ray Imaging Technology) is an 80x80 array of 250 micron pixels sensitive in the 4--80 keV band and capable of a full frame readout rate of 10 kHz. HEXITEC is being developed in part for solar astrophysics, where observations of extremely bright solar flares often cause pileup in current detectors.

HEXITEC's small 250 micron pixels are the smallest independently read out pixels currently available, and are well matched to the few arcsecond PSF produced from current and next generation hard X-ray focusing optics. The Rutherford Appleton Laboratory has developed the ASIC used for HEXITEC, which is then bonded to 1-2 mm thick CdTe.

NASA's Goddard and Marshall Space Flight Centers are collaborating with RAL to develop these detectors for use with hard X-ray focusing telescopes for astronomy and have achieved spectral resolutions better than 1 keV at 60 keV. We present recent developments from the HEXITEC program and report on its current performance.

9915-51, Session 11

Persistence measurements and photometric impact of intra-pixel variations on a Euclid HAWAII-2RG at ESTEC

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In the frame work of the ESA's Cosmic Vision program, the Euclid mission has the objective to map the geometry of the Dark Universe. Galaxies and clusters of galaxies will be observed in the visible and near-infrared wavelengths by an imaging and spectroscopic channel. For the Near Infrared Spectrometer instrument, the state-of-the-art HAWAII-2RG detectors will be used, associated with the SIDECAR ASIC readout electronic.To characterize the persistence performance and the photometric impact of the intra-pixel variations, a test bench in the Payload Technology Validation Section at ESTEC has been designed, tested and validated.This publication describes the test set up developed to measure the persistence by projecting flat field over a Euclid HAWAII-2RG and the associated results for different illumination level, temperature and exposure time.This publication will describes as well the set up used to project a spot on the detector to measure the photometric impact of the intra-pixel variation. The results of the sub-pixel spot scan on the photometric impact will be as well presented.

9915-52, Session 11

HgCdTe calibrated photodiodes for quantum efficiency measurements in IR spectral range

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Absolute measurements of quantum efficiency (QE) in IR domain on focal plane arrays are extremely difficult because of the lack of calibrated photodiodes in this spectral range. Actually, the only calibrated photodiodes available commercially, with a good accuracy, are based on Silicon (Si) technology and so exhibit a cut-off wavelength close to 1.1µm.

We propose in this paper a method to calibrate the MCT photodiodes made at CEA-LETI. The aim of this method is to use the capability of MCT to be sensitive in the visible range, independently of the cut-off wavelength. Moreover we know that the Quantum efficiency is constant in the IR and visible domain. We therefore feel that it is possible to calibrate MCT IR photodiode in the visible range where Si diodes can be used as reference.

The relative spectral response of the photodiodes is measured with a FTIR system, and the absolute calibration is performed with a calibrated black body. Then, the validation of this absolute calibration is assessed by thinning a photodiode to get uniform sensitivity from the IR to the visible spectral range, measure its absolute responsivity with the black body in the IR range and again in the visible against a calibrated Si photodiode. This paper will present the experimental setup as well as results on the calibration of photodiodes at 12.5µm cutoff.

9915-53, Session 11

Persistence characterization and comparison of European large format array NIR detectors

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The Payload Technology Validation Section (SRE-FV) at ESTEC has the goal of validating new technology for future or on-going missions. In this framework, a test set up to facilitate the characterisation of near-infrared (NIR) detectors has been created. A current technology development activity at ESA, the European Large Format Array (LFA), is being undertaken by a small team with the goal of creating a full NIR photon-to-SpaceWire detection system. In the context of the NIR European LFA, a number of detectors are tested in order to identify a suitable epitaxial technology and supplier. We report on the characterisation progress of the LFA detectors, for which a series of rigorous tests have been performed on four different detectors provided by CEA/LETI; two LPE and two MBE. Experimental techniques and results will be presented, in particular regarding the persistence/latency effect observed in such detectors and its dependency on temperature, illumination duration and illumination level. These effects are investigated by producing a flat field from an array of five LEDs integrated into the vacuum chamber and the results can be compared to data from HAWAII-2RG detectors from the Euclid project. Relevant conclusions will be presented and the effectiveness of mitigation strategies will be explored. Other properties and effects under investigation and discussed in this report include conversion gain, dark current and inter-pixel coupling. The impact of irradiation on the detector performance is investigated here and the results from the different detectors are then compared to support the on-going development of the LFA activity.

9915-55, Session 11

Flexible focal plane arrays for VIS/NIR wide field instrumentation

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LAM and CEA-LETI are developing the technology of deformable detectors, for VIS or NIR applications. Such breakthrough devices will be a revolution for future wide field imagers and spectrographs, firstly by improving the image quality with better off-axis sharpness, resolution, brightness while scaling down the optical system, secondly by overcoming the manufacturing issues identified so far and by offering a flexibility and versatility in optical design.

The technology of curved detectors can benefit of the developments of active and deformable structures, to provide a flexibility and a fine tuning of the detectors curvature by thinning the substrate without modifying the fabrication process of the active pixels. We present studies done so far on optical design improvements, the technological demonstrators we developed and their performances as well as the future five years roadmap for these developments.